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NUTRIENT DYNAMICS IN THE NORTHERN GULF OF ALASKA AND PRINCE

WILLIAM SOUND: 1998-2001

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**NUTRIENT DYNAMICS IN THE NORTHERN GULF OF ALASKA AND PRINCE
WILLIAM SOUND: 1998-2001**

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DISSERTATION**

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Of the University of Alaska Fairbanks
In Partial Fulfillment of the Requirements
For the Degree of**

DOCTOR OF PHILOSOPHY

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ABSTRACT

The northern Gulf of Alaska (GOA) shelf is a productive coastal region that supports several commercially important fisheries. The mechanisms supporting such high levels of productivity over this shelf are not understood, however, since it is a downwelling-dominated shelf. In an effort to understand the mechanisms underlying such high biological productivity, nutrient distributions were determined 25 times throughout 1998, 1999, 2000, and 2001 from over the northern GOA shelf and in Prince William Sound (PWS).

Deep water (>75 m) nitrate, silicate and phosphate concentrations were positively correlated with salinity indicating an offshore nutrient source. The average annual cycle was established, in which nitrate, silicate and phosphate responded seasonally to physical and biological processes. Ammonium concentrations were generally low and uniform (<1.2 μM) with occasional patches of higher concentrations. During each summer, an onshore flux of dense nutrient-rich bottom water onto the shelf was evident when the downwelling relaxed. This seasonal flux created nutrient reservoirs over the deeper shelf regions that were eventually mixed throughout the water column during the winter months. This annual evolution may be vital to the productivity of this shelf.

A large degree of interannual variability was found during the study, which included El Niño (1998) and La Niña (1999) years. Spring phytoplankton biomass over the shelf was highest in 2000 when the upper waters were nutrient enriched and strongly stratified. The highest phytoplankton biomass was measured in May 1999 during the passage of a slope eddy, which demonstrated the potential of these phenomena to greatly enhance primary productivity. A large degree of spatial variability was also found, both cross-shelf and along-shelf. Hinchinbrook Canyon was found to consistently have high salinity, nutrient-enriched bottom waters suggesting it plays an important role in the transport of slope waters onto the shelf and probably into PWS. Along-shelf trends were found in the upper coastal waters in the winter and spring, with higher salinities, temperatures, and nutrient concentrations upstream of PWS. The nutrient dynamics were

similar in PWS and over the shelf/slope in 2001; however, nutrient drawdown, followed by depletion, and the spring bloom appeared earlier and stronger in PWS.

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Chapter 1. General Introduction

1.1 Reasons for interest

The Gulf of Alaska (GOA) shelf is a very productive region insofar as its primary production and food web support several commercially important fisheries such as salmon, pollock, and halibut. However, the reasons for this high productivity are not clearly understood, considering it is a deep, coastal downwelling shelf. Nutrients, incident radiation, and the presence of stratification are all necessary for phytoplankton growth, which is the foundation of a productive ecosystem (Lalli and Parsons, 1993). Shelf regions at lower latitudes along the eastern edge of the Pacific Ocean support productive ecosystems due to wind-driven upwelling, which regularly replenishes the euphotic zone with nutrients from deep nutrient-rich waters. The GOA, on the other hand, only experiences weak upwelling during the summer months when the cyclonic along-shore winds temporarily relax. Hence, during the majority of the year the GOA is dominated by a downwelling circulation system.

Little research had been performed to examine the distributions and concentrations of the major nutrients in the northern GOA prior to 1997. Therefore, the sources and distributions of the major nutrients in this region were relatively unknown. The nutrient data from this research, part of the Gulf of Alaska (GOA) Global Ocean Ecosystem Dynamics (GLOBEC) Long Term Observation Program (LTOP), represent the first systematic yearly record of major nutrient concentrations across the northern GOA shelf. These data provide an initial examination of the annual, interannual, and spatial distributions and concentrations of nitrate, silicate, phosphate, and ammonium relative to the physical properties and phytoplankton biomass across the northern GOA shelf and slope.

1.2 The general hydrography of the northern Gulf of Alaska

1.2.1 Atmospheric dynamics

An energetic winter season dominates the annual atmospheric cycle over the GOA. The Aleutian Low pressure region, caused by frequent, intense storms (low-pressure systems), travels from the Bering Sea over the Alaska Peninsula into the GOA in the fall bringing with it maximum cyclonic winds, which commence in November and continue through January (Ingraham et al., 1976). This wind regime along the GOA coast generates downwelling, which is most intense during the winter months (Reed and Schumacher, 1986). During these months, the along-shore winds induce maximum Ekman onshore transport at the surface producing downwelling which traps the relatively low salinity water against the coast (Ingraham et al., 1976). Regional winds typically blow westward along the coastline throughout the year except for one or two months in the summer, when the coastal zone experiences slight upwelling as the along-shore winds relax when the North Pacific High dominates (Reed and Schumacher, 1986). Therefore, the atmospheric circulation undergoes a strong annual cycle, which is reflected in the annual cycle of water properties and water circulation around the GOA and over the shelf.

The shelf water properties in this region have two extremes as described by Royer (1975). During winter, the intensification of cyclonic atmospheric circulation over the GOA produces easterly coastal winds and downwelling. The winds and thermohaline processes also contribute to vertical mixing of the water column, such that shelf waters under winter conditions are vertically well-mixed with elevated salinities and low temperatures. During summer, stratification increases due to freshwater inputs and insolation, as the coastal winds decrease allowing the downwelling to relax and create a weak upwelling response. The shelf waters under summer and fall conditions are stratified in temperature, salinity, and density with surface temperatures at their maximum and salinities at their minimum within the annual cycle.

On longer time scales, evidence of interannual variations in the GOA flows and properties resulting from the climatic variability of the El Niño/Southern Oscillation

(ENSO) and the Pacific Decadal Oscillation (PDO) has been found. Throughout the twentieth century, PDO events, or phases, persisted for 20 to 30 years while ENSO events persisted 6 to 18 months (Mantua, 1999). The most recent ‘warm’ phase of the PDO appears to have lasted from 1977 through 1999 then entered into a ‘cool’ phase (NASA, 2005). In the tropical Pacific, a La Niña was present in 1995-1997, followed by a strong El Niño in 1997-1998, which was followed by another La Niña in 1998-2001 (Schwing et al., 2002). Evidence of the PDO is most visible in the North Pacific with secondary signatures in the tropics, but the opposite is true for ENSO. Researchers recently discovered that ‘warm’ phases of the PDO enhance coastal ocean biological productivity in various Alaskan waters, but at the same time inhibit productivity off the west coast of the United States, while ‘cool’ phases have the opposite pattern. During the most recent El Niños of 1977, 1987, and 1998, the winter air temperatures were relatively high and precipitation was greater in the northern GOA (Stabeno et al., 2004). These phase changes of ENSO and PDO encompass the years these data were collected and could potentially account for interannual variability found in the oceanographic properties of the northern GOA.

1.2.2 Gulf of Alaska

The Gulf of Alaska (GOA) is dominated by a large-scale cyclonic subarctic gyre (Fig. 1.1) (Reed and Schumacher, 1986). This counter-clockwise flow around the gulf induces horizontal divergence and upwelling at the center of the gyre (Ingraham et al., 1976). This creates an upward flux of water from a southerly origin, with high salinity, low temperature, low dissolved oxygen, and high nutrient concentrations (Favorite et al., 1976). The gyre, as described by Reed and Schumacher (1986), consists of the North Pacific Current, which flows eastward across the North Pacific in the vicinity of 45-50°N latitude, and then bifurcates into the Alaska Current and the California Current (Fig. 1.1). The Alaska Current flows northward and then westward along the continental slope. The width of the Alaska Current varies from 400 km wide at the head of the gulf to less than 100 km wide west of Kodiak Island. The Alaska Current is considered a typical eastern boundary current that is rich in eddies and meanders (Stabeno et al., 2004). West of

~150°W, the Alaska Current is considered the Alaskan Stream since the flow is a high-speed narrow, boundary flow. The Alaskan Stream continues along the southern edge of the Aleutian Islands where the flow either turns north into the Bering Sea through Aleutian Island passes or south completing the GOA gyre (Favorite et al., 1976) (Fig. 1.1). The flow at the head of the gulf within the Alaska Current averages ~5 cm sec⁻¹ and reaches peak speeds of approximately 30 cm sec⁻¹, whereas the flow within the Alaskan Stream is much larger with a mean of around 20 cm sec⁻¹ and peak speeds of ~100 cm sec⁻¹ (Reed and Schumacher, 1986).

The Alaska Coastal Current (ACC) is a distinct flow along the coast of the GOA (Fig. 1.1). This flow has a strong seasonal signal with maximum speeds in the fall, September and October, when precipitation and continental runoff reach the annual maximum (Royer, 1982). The low salinity water within the ACC is predominantly confined along the coast by downwelling favorable winds, resulting in baroclinic flow along the coast and a very stable water column. Throughout the year, the surface salinity of the coastal waters may change by up to seven parts per thousand. The surface temperatures also vary by about seven degrees Celsius, although this temperature range only induces a shift of about one sigma-t unit in density (1 kg m⁻³). On the other hand, the range in salinity alters density by four to five sigma-t units (kg m⁻³) (Reed and Schumacher, 1986). Therefore, changes in salinity exert a much larger influence on the density distributions and baroclinic flow over the shelf (Royer, 1981). The storage of precipitation as ice and snow throughout the winter months along the GOA coast determines to a great extent the amount of dilution in the coastal waters the following spring and summer (Ingraham et al., 1976). Royer (1982) concluded that the narrow, intense coastal flow is the result of salinity gradients that are controlled by freshwater discharge and subsequent modification by the winds. The coastal runoff produces a seasonal offshore movement of the surface intersection of the 32 psu isohaline, which moves as far as 200 km offshore in the summer during the relaxation of the downwelling favorable winds relative to its winter position (Ingraham et al., 1976). The coastal circulation is also influenced by the locations and flows of the Alaska Current/Alaskan

Stream, broad scale cross-shelf Ekman transport, and episodic entrainment from the slope (Stabeno et al., 2004).

The flows on the northern GOA shelf are unusual in that they travel over a relatively broad, 75-150 km, and deep, 150-250 m, continental shelf (Royer and Muench, 1977) (Figs. 1.1 and 1.2). Numerous silled and unsilled fjords, embayments, capes, and island groups complicate the coastline (Reed and Schumacher, 1986). The shelf flows are further modified by topographic steering due to the complex bathymetry which includes numerous ridge and trough features (Royer and Muench, 1977). The submarine canyons and troughs, such as Hinchinbrook Canyon (Sea Valley), Bainbridge Trough and Resurrection Canyon, influence the bottom flows and potentially provide conduits for the flow of deep, dense, nutrient-rich waters onto the shelf (Fig. 1.2). Drifter trajectories in the ACC showed the coastal flow to be relatively organized between Icy Point and Kayak Island and downstream of Gore Point, but the flow west of Kayak Island and along the Kenai Peninsula was found to be convoluted with mesoscale activity, likely due to the complex topography (Stabeno et al., 2004).

Increasing evidence shows that small, transient eddies frequent the GOA shelf in addition to very large, long lasting eddies which travel along the continental slope for two to three years (Crawford and Whitney, 1999). Recent observations of large, anticyclonic mesoscale eddies showed that they are generated in the Alaska Current during the winter months off the eastern coast of the GOA between Vancouver Island and Kayak Island. These eddies are collectively referred to as Sitka eddies if they form near Sitka off the Alaska Panhandle, Haida eddies if they form off the west coast of Queen Charlotte Islands, or Yakutat eddies if they form offshore of Yakutat Bay (Crawford, 2002; Okkonen, 2001). These eddies propagate offshore towards the interior of the Alaska Gyre in directions between south-southeast and north-northwest and can exist for several years, while traveling as far as 1000 km from their origin (Crawford, 2002; Whitney & Robert, 2002,). The Yakutat eddies are the only ones which propagate into the Alaska Stream (Okkonen, 2001). Researchers recently realized that these eddies are generally larger during ENSO winters when the northward, along-shore wind stresses along the

eastern GOA are stronger, which promotes strong downwelling along the British Columbia -Alaska coast. The Haida eddies have been found to transport shelf waters, which are fresher and higher in nutrients and plankton, to the HNLC (high nutrient low chlorophyll) waters of the middle-gulf, increasing the productivity of the open ocean (Whitney & Robert, 2002). Large eddies have been observed in the northern GOA within our study region following the continental slope and the Aleutian Trench south of the Aleutian Islands. Okkonen et al. (2003) analyzed the effects of anticyclonic eddies propagating along the continental shelf in the northwestern GOA to find that they altered the structure of the shelf break front which influenced the shelf-slope exchange of water mass properties. They further concluded that these mesoscale features are seasonally modulated and interannually variable. Evidence of smaller eddy activity in the coastal flow over the shelf was also found. For example, eddies have been observed off the west side of Kayak Island, just east of the study area (Reed and Schumacher, 1986). Royer et al. (1979) concluded a permanent anticyclonic eddy exists in the lee of Kayak Island that is sustained by the coastal current, coastline, and bathymetry. The slope eddies that pass through the northern GOA have been found to influence the physical properties over the shelf break and slope; therefore we can assume that eddy activity, either over the shelf or over the slope, has an effect on the chemical and biological properties.

1.2.3 Prince William Sound

Prince William Sound (PWS) is described as a small, subarctic, semi-enclosed sea surrounded by mountains, glaciers, coastal rivers, and numerous bays and fjords (Muench & Schmidt, 1975) (Figs. 1.1 and 1.2). PWS is located north of the GOA and is connected to the GOA by two major passages: Hinchinbrook Entrance and Montague Strait. Vaughn et al. (2001) deduced that the processes that control the physical environment in PWS include tidal motions, responses to transient wind stresses associated with weather cycle, seasonal winds, seasonal heating and cooling, precipitation and evaporation, river/glacial runoff, exchange with the northern GOA, and longer term events (ENSO and PDO). Furthermore, Niebauer et al. (1994) describe the circulation in PWS as the portion of the ACC on the GOA shelf that flows through PWS that is strongly mediated by

seasonal and interannual variations in winds and freshwater runoff as well as by local topography both inside and outside the sound. Vaughn et al. (2001) found that in central PWS (1994-1998), the basin-scale circulation throughout the year was either ill-defined (dominated by eddies) or cyclonic. Researchers generally assumed that PWS was dominated by a throughflow-driven circulation, where the ACC flowed into PWS at Hinchinbrook Entrance then out of PWS at Montague Strait with some seasonal changes due to wind-forcing and precipitation (Niebauer et al., 1994; Royer, 1979). Recent model results by Bang and Mooers (2003) demonstrated that throughflow in PWS is not one-way flow from Hinchinbrook Entrance to Montague Strait. Instead Hinchinbrook Entrance is the major passage, which can have both inflow and outflow simultaneously, while Montague Strait is the minor passage that is only capable of one flow direction most of the time. Clearly more research needs to be performed to fully understand the physical connections between PWS and the northern GOA.

In the deeper waters of PWS, the seasonal intrusion of dense slope water onto the northern GOA shelf and into PWS provides annual deep-water renewal (Royer, 1975). This renewal occurs over the summer months when the relaxation of coastal downwelling allows deep, dense water to rise above the shallow sill (~180 m) and flow into PWS (Niebauer et al., 1994).

Over the spring and summer months, stratification in the upper water column develops due to surface warming and freshening; however, seasonal stratification does not develop simultaneously throughout PWS and varies interannually (Vaughn et al., 2001). Eslinger et al. (2001) studied the plankton dynamics in response to the springtime physical conditions in PWS and found that the spring blooms fit into the following two categories. (1) During relatively calm, warm springs, the water column stratifies quickly forming a shallow surface mixed layer that is separated from the lower water column by a strong pycnocline. This stratification produces brief, intense bursts of productivity where nutrients are quickly depleted. A large portion of the phytoplankton production sinks out of the surface waters and is not consumed by the zooplankton community. (2) During cooler, stormier springs, stratification occurs briefly between storms resulting in smaller

bursts of productivity. Frequent storms mix the upper water column reducing phytoplankton concentrations while increasing near-surface nutrient concentrations. This process repeats until stratification by heating and freshwater runoff stabilizes the upper water column. Then the bloom continues until nutrients are depleted. Due to the longer, less intense spring blooms, a larger portion of the phytoplankton production is transferred to the zooplankton population. The authors conclude that during a relatively short, critical period each spring the meteorological conditions play a dominant role in the dynamics of the phytoplankton and zooplankton populations for the rest of the spring and early summer. Earlier studies in Port Valdez by Goering et al. (1973) found that the annual cycle of primary productivity peaks in April and is classically nitrogen limited during the summer months. Eslinger et al. (2001) further found that the spring bloom phytoplankton community was dominated by centric diatoms. In May when the diatom bloom became nitrogen limited, small flagellates constituted a larger portion of the diminishing phytoplankton community.

1.3 Methods

1.3.1 Collection methods

The data discussed throughout this dissertation were collected during twenty-five cruises in 1998, 1999, 2000, and 2001 aboard the *R/V Alpha Helix* as part of the Global Ocean Ecosystem Dynamics (GLOBEC) Gulf of Alaska (GOA) Long Time Series Observation Program (LTOP). The cruises took place in March, April, May, July, August, October, and December (Table 1.1). Several shelf transects were occupied during each cruise with the Seward Line given the highest priority. The Seward Line (GAK) is a cross-shelf transect which encompasses both the shelf waters within the Alaska Coastal Current (ACC) and the slope waters within the Alaskan Stream (Fig. 1.3). This transect allowed for preliminary observations of the seasonal cycles and interannual variability of the chemical, physical, and biological properties across the northern GOA shelf/slope, as discussed in Chapter 2. Additional cross-shelf transects, including Cape Fairfield (CF), Cape Cleare (CC), Cape Cleare Southeast (CCSE), Cape Cleare

Southwest (CCSW), Ragged Island (RI), Pye Island (PI), Copper River (CR), Cape Suckling (CS), and Gore Point (GP) were occupied, time and weather permitting, as these transects provided more thorough sampling of the shelf waters within the ACC upstream and downstream of the Seward Line (Fig. 1.3). Cross-shelf transects near the entrances to Prince William Sound (Hinchinbrook Entrance (HE), Along Hinchinbrook Canyon (AHC), and Prince William Sound West (PWSW)) and transects within Prince William Sound (Hogan Bay (HB), Montague Strait (MS), Knight Island Passage (KIP), Prince William Sound (PWS)) were also occupied, time and weather permitting, to sample the shelf waters entering, exiting, and passing through PWS (Fig. 1.3). These additional transects are discussed in Chapter 3.

Nutrient samples were collected at stations along the transects with a Sea Bird 911 Plus CTD/rosette sampler with twelve five liter Niskin bottles. Samples were taken every 10 m in the upper 50 m. Samples below 50 m were taken at varying intervals throughout the water column, depending on station depth and variations in the temperature, salinity, or fluorescence profiles. Samples collected in 1998 were frozen for later analysis of nitrate, nitrite, silicate, phosphate, and ammonium in the laboratory. Samples collected in 1999, 2000, and 2001 were analyzed aboard ship for nitrate, nitrite, silicate, phosphate, and ammonium shortly after sampling. A Wet Labs fluorometer attached to the CTD/rosette system provided chlorophyll fluorescence profiles at each station. Discrete upper water column samples were also collected for *in vitro* chlorophyll analysis.

1.3.2 Chemical analyses

The chemical analyses of nitrate, nitrite, silicate, phosphate, and ammonium were performed using colorimetric techniques on Technicon AutoAnalyzer II and Alpkem model 300 continuous nutrient analyzers (Whitledge et al., 1981). These instruments allow for rapid analysis of up to six parameters on a large number of samples. Water samples collected in polyethylene scintillation vials were pumped into a manifold where

the appropriate chemicals were added and mixed to produce an observable color which was measured in a colorimeter.

1.3.2.1 Nitrate and nitrite

Nitrite, NO_2^- , concentrations were determined by the Greiss reaction in which sulfanilimide, dissolved in diluted hydrochloric acid, was first added to the water sample as the diazotizing agent. N-(1-Naphthyl) ethylenediamine dihydrochloride (NNED) was then added as the coupling reagent which reacted with NO_2^- to produce an extremely pink diazo dye with an absorption maximum at 540 nm (Bendschneider and Robinson, 1952).

Nitrate, NO_3^- , concentrations were also determined using the Greiss reaction. However, this nutrient analysis required an additional step. The NO_3^- within the water samples was first reduced to NO_2^- as it passed through a cadmium-copper reduction coil (Wood et al., 1967). Imidazole buffer was added before the cadmium column to eliminate any interference due to iron, copper, or other metals (ALPKEM Corporation, 1986). In addition, nitrogen gas was supplied to this channel as the segmentation gas to maintain a constant pH by minimizing the formation of cadmium hydroxide from the reaction of oxygen on the reactor wall (ALPKEM Corporation, 1986). Sulfanilimide and NNED were then added to the samples, which reacted with NO_2^- to form the pink diazo dye measured in the colorimeter (Wood et al., 1967; Whitledge et al., 1981). Consequently, this channel measured both NO_3^- and NO_2^- ; therefore, the NO_2^- concentration was subtracted from the $\text{NO}_3^- + \text{NO}_2^-$ concentration for each sample to determine the NO_3^- concentration.

1.3.2.2 Silicate

Orthosilicic acid, Si(OH)_4 , or reactive silicate, $(\text{SiO}_2)_n + \text{water}$, (where $n = 1, 2, 3, 4$) concentrations were determined by a set of three reactions. The first reaction involved ammonium molybdate, dissolved in a dilute sulfuric acid solution, which transformed Si(OH)_4 into silicomolybdic acid (Armstrong et al., 1967). Tartaric acid was added to prevent interference by phosphomolybdate and arsenomolybdate, which may have formed in the previous reaction, by dissolving these complexes (Mullin and Riley, 1955).

The silicomolybdic acid was then reduced by the addition of stannous chloride to molybdenum blue, which has an absorption maximum of 820 nm (Whitledge et al., 1981).

1.3.2.3 Phosphate

Orthophosphate is present in various ionic forms in seawater: H_2PO_4^- , HPO_4^{2-} , or PO_4^{3-} . These concentrations were determined by treating the samples with an ammonium molybdate/potassium antimonyl tartrate (KAT) solution and ascorbic acid. This solution reacts with phosphate by reducing the phosphate ions into phosphomolybdic acid, which contains antimony and phosphate in a 1:1 atomic ratio. The samples were heated to 30°C to accelerate the reaction. This new complex, called phosphomolybdenum blue, is a blue-purple color with an absorption maximum of 880 nm (Murphy and Riley, 1962).

1.3.2.4 Ammonium

Ammonium, NH_4^+ , concentrations were determined by the Berthelot reaction (Slawyk and MacIsaac, 1972). As the water samples passed through the manifold a dilution complex was added which consisted of sodium citrate and sodium hydroxide (Patton and Crouch, 1977). This buffer solution maintained a basic pH which ensured both rapid formation and minimal decomposition of the first intermediate (Patton and Crouch, 1977). Next, reagent A was added, which was a solution of phenol and sodium nitroprusside (Slawyk and MacIsaac, 1972). The sodium nitroprusside acted as a catalyst as it increased the sensitivity and rate of the reaction (Patton and Crouch, 1977). Reagent B was then added, which was a basic solution of hypochlorous acid (Chlorox) and sodium hydroxide. Finally, the samples were heated to 60°C. Altogether, the hypochlorous acid and phenol reacted with NH_4^+ in an aqueous alkaline solution of sodium citrate and sodium hydroxide to produce indophenol blue (Whitledge et al., 1981). The indophenol blue is an intensely blue chromophore with an absorption maximum at 637 nm (Whitledge et al., 1981). This procedure is a modification of the Slawyk and MacIsaac (1972) procedure.

1.3.2.5 Chemical preparation

The chemical solutions and standards were prepared with deionized water (DIW) treated by a Millipore ultrapure water system. All the chemical solutions and stock standard solutions were stored in a refrigerator except those that should not be refrigerated. Nutrient standards were prepared daily from stock standard solutions that were prepared approximately twice a year.

When the standard and sample peaks were manually read and entered into a computer program called Symphony the following protocol was used. Nitrate and silicate were prepared together as a set of standards, S-1's, with the following concentrations: 5.0, 15.0, 25.0, 35.0, and 45.0 μM . Nitrite, phosphate, and ammonium standards were prepared as another set of standards, S-2's, with the following concentrations: 0.5, 1.5, 2.5, 3.5, and 4.5 μM . A sync standard was also prepared daily, which included all five nutrients at the highest concentration or twice the highest concentration to check that the chemical channels were separating the nutrients and working properly. The standard and sample peaks were recorded on strip charts to an accuracy of ± 0.01 volts with a full-scale range of five volts. The two sets of five standards, plus the occasional sync standard, were run initially then routinely between sample runs. The standards provided a series of absorption peaks for each known nutrient concentration, yielding a slope, which was then used to calculate the seawater sample concentrations.

When the standard and sample peaks were read using an onboard computer program, called the Nutrient Analysis Program (NAP), connected to the auto-analyzer photometers, the following protocol was used. Nitrate, nitrite, silicate, phosphate, and ammonium were prepared together daily as a set of standards, S1-S5, along with a sync, using the same concentrations listed in the previous protocol. All five standards were run together initially then intermittently throughout the rest of the day. Three to five standards were sampled at the beginning of each run. The NAP program calculated a slope for each nutrient using the standards sampled at the beginning of each run then

applied it to the samples in that run; therefore, new slopes were calculated at the beginning of each run.

During 1999, when the samples were analyzed onboard, standards from each set were run systematically at the beginning of the sample runs to survey the accuracy and reproducibility of the Technicon AutoAnalyzer II. These standards were used to calculate the percent error, standard deviation, and 95% confidence intervals for each channel averaged over each cruise and over the year. The yearly average percent error for all five channels was between 4% and 10%, with the nitrate, silicate, and nitrate + nitrite channels being the most accurate and the ammonium and phosphate channels slightly less accurate. The yearly averaged 95% confidence interval produced ranges of $\pm 0.09 \mu\text{M NO}_2^-$, $\pm 0.19 \mu\text{M NH}_4^+$, $\pm 0.25 \mu\text{M PO}_4^{3-}$, $\pm 0.78 \mu\text{M NO}_2^- + \text{NO}_3^-$, and $\pm 1.35 \mu\text{M Si(OH)}_4$. Duplicates were also run occasionally on seawater samples, which presented similar high levels of reproducibility. Throughout 2000 and 2001, duplicates and replicates were also run occasionally to ensure accuracy and reproducibility.

1.3.2.6 Chlorophyll *a*

Chlorophyll *a* concentrations were determined using an acetone/DMSO extraction procedure measured on a Turner Designs model 10AU fluorometer (Shoaf and Lium, 1976). Onboard, a known amount of seawater, commonly 1.0 liter, was filtered through a 25 or 47 cm GF/F glass microfibre filter with a nominal pore size of $0.7 \mu\text{m}$. The filters were then stored in a freezer in labeled aluminum foil envelopes. Onshore, the pigments were extracted from the filters by submerging the filters in an acetone/DMSO solution overnight in a freezer (Shoaf and Lium, 1976). The samples were then brought to room temperature, mixed vigorously, and read in a fluorometer to determine chlorophyll *a* concentrations (a modification of Parsons et al., 1984). Fluorometers were calibrated with commercial standards over a range of 0.1 to $150 \mu\text{g chl } a \text{ l}^{-1}$.

1.3.2.7 Contouring

The temperature, salinity, and nutrient concentrations were contoured for each cruise across the Seward Line and along the various transects using the contouring

program, Ocean Data View (ODV). These contour plots display the discrete sample depths with dots and the CTD data taken in one meter intervals in vertical black lines. Time series contour plots at individual stations were also generated with ODV, and likewise display the dots and vertical lines showing sampling locations.

1.4 Objectives

The objectives of this dissertation were as follows:

1. To establish an average annual nutrient cycle for the northern GOA shelf/slope in order to determine the degree of nutrient limitation in this region and to identify potential nutrient sources. (Chapter 2)
2. To examine the extent of cross-shelf and interannual variability in the nutrient dynamics. (Chapter 2)
3. To calculate new production rates for various shelf regimes and compare those to other areas. (Chapter 2)
4. To determine the degree and cause of spatial variability in the nutrient distributions and dynamics across and along the northern GOA shelf. (Chapter 3)
5. To compare the nutrient dynamics between the northern GOA shelf/slope and Prince William Sound and to determine any prevailing spatial nutrient dynamics in Prince William Sound. (Chapter 3)
6. To describe the effect of slope eddies on the northern GOA shelf/slope nutrient dynamics. (Chapter 3)

1.5 References

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Table 1.1 GLOBEC LTOP cruises throughout 1998, 1999, 2000, and 2001.

1998	1999	2000	2001
8 – 15 Mar	14 – 21 Mar	6 – 14 Mar	2 – 13 March
31 Mar – 7 Apr	12 – 19 Apr	17 – 25 Apr	3 – 14 April
7 – 14 May	6 – 13 May	16 – 25 May	4 – 14 May
10 – 17 July			28 June – 9 July
	26 Aug – 2 Sept	12 – 22 Aug	30 July – 8 Aug
2 – 9 Oct	5 – 12 Oct	2 – 10 Oct	9 – 18 Oct
1 – 8 Dec	30 Nov – 7 Dec	30 Nov – 8 Dec	4 – 11 Dec

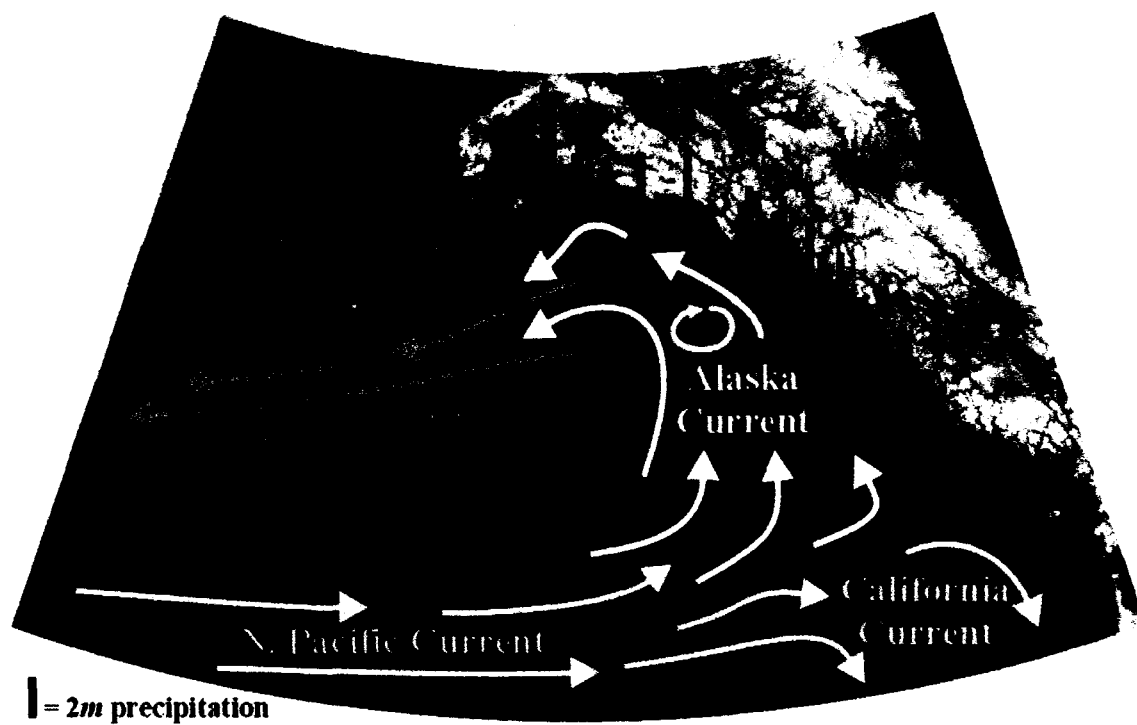


Figure 1.1 Gulf of Alaska surface currents (arrows) and mean annual precipitation totals (black vertical bars).

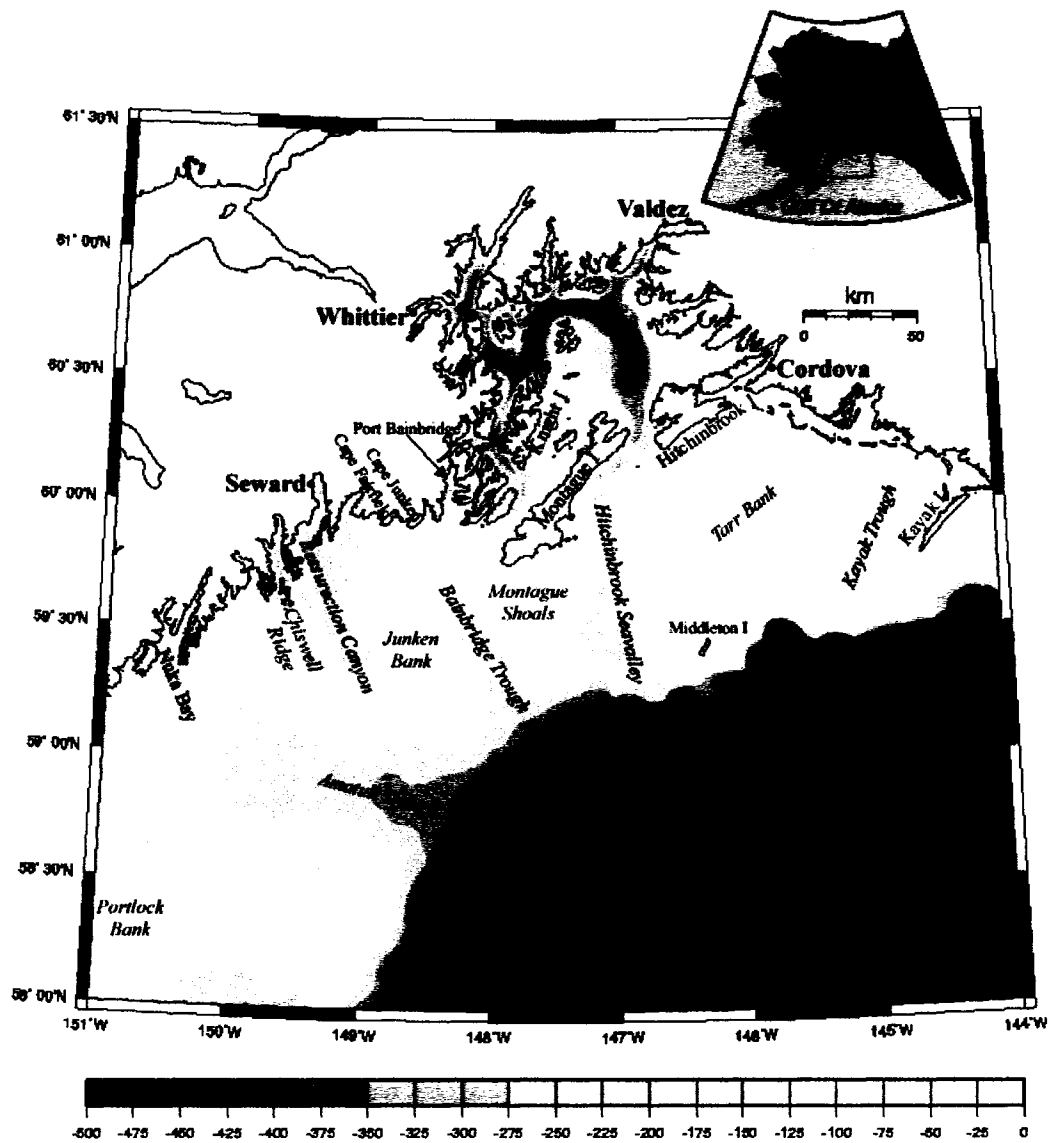


Figure 1.2 Bathymetry and nomenclature of the northern Gulf of Alaska and Prince William Sound.

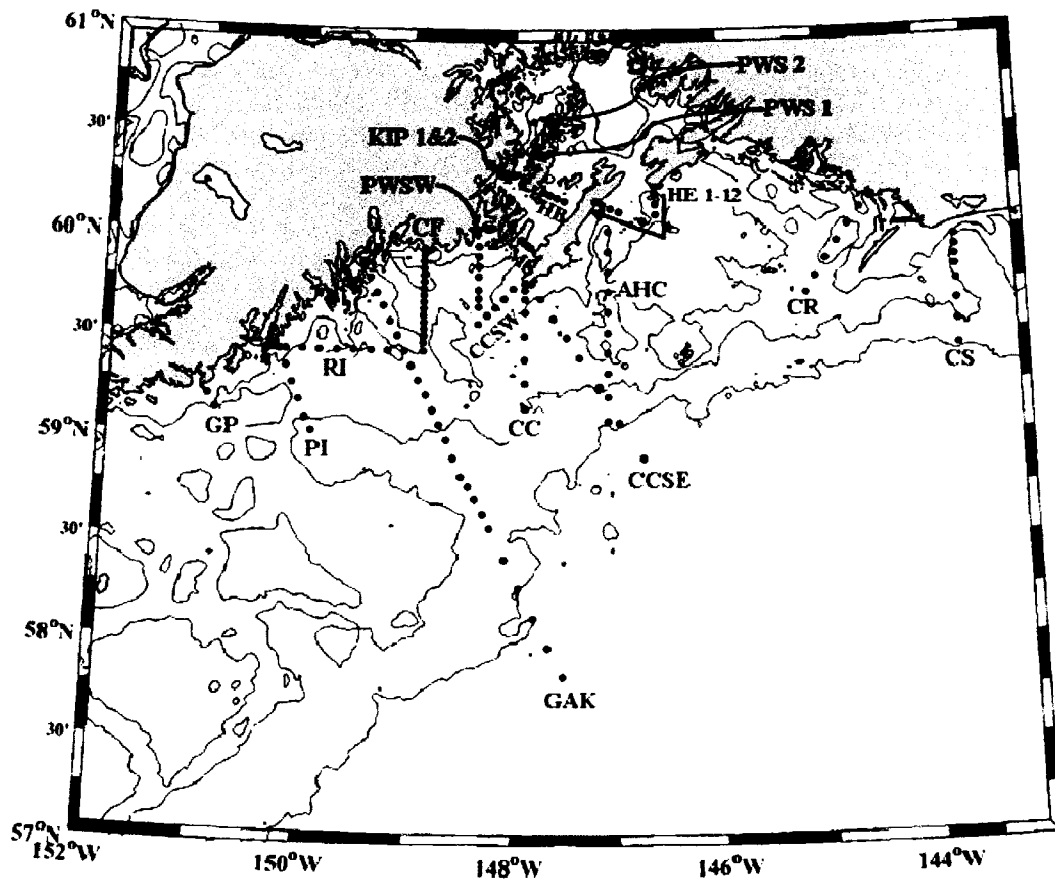


Figure 1.3 The GLOBEC transects with station number increasing with distance offshore over the shelf/slope, except for the HE stations which increase along the arrow. The individual Prince William Sound stations are labeled and the stations along HB and MS increase from northwest to southeast. Abbreviated transect names are described in Chapter 1 on pages 8-9.

Chapter 2. Seasonal and interannual variability in the distribution of nutrients and chlorophyll *a* across the Gulf of Alaska shelf: 1998-2000*

2.1 Abstract

The northern Gulf of Alaska shelf is a productive coastal region that supports several commercially important fisheries. The mechanisms supporting such high levels of productivity over this shelf however are not understood since it is a downwelling-dominated shelf. Furthermore, the annual nutrient cycle in this region was completely unknown prior to this research. In an effort to understand the mechanisms driving such high biological productivity cross-shelf nutrient distributions were sampled 18 times throughout 1998, 1999 and 2000. Deep water (>75 m) nitrate, silicate and phosphate were positively correlated with salinity indicating an offshore nutrient source. The average annual cycle was established, in which nitrate, silicate and phosphate responded seasonally to physical and biological processes. Ammonium concentrations were generally low and uniform (<1.2 μM) with occasional patches of higher concentrations. Throughout the summer months, the upper 10-20 m across the shelf was depleted of nitrate, silicate and phosphate over the inner and middle shelves and depleted of nitrate and phosphate over the shelf break and slope; however, just below this nutrient-poor layer the water column was nutrient-replete. During each summer, there was an onshore flux of dense nutrient-rich bottom water onto the shelf when the downwelling relaxed. This seasonal flux created a nutrient reservoir near the bottom of the inner and middle shelves. The reservoir was eventually mixed throughout the water column during the winter months. This annual evolution may be vital to the productivity of this shelf.

*Childers, A.R., Whitledge, T.E., Stockwell, D.A., 2005. Seasonal and interannual variability in the distribution of nutrients and chlorophyll *a* across the Gulf of Alaska shelf: 1998-2000. Deep Sea Research II Special Issue on the Northeast Pacific GLOBEC Program 52, 193-216.

There was a large degree of interannual variability among the three years, which included El Niño (1998) and La Niña (1999) years. Nutrient concentrations and chlorophyll were generally highest in 2000, except in May 1999, when a large eddy traveling along the continental slope greatly enhanced phytoplankton chlorophyll biomass. Daily new production estimates based on nitrate disappearance averaged over the spring-summer season ranged from 2.46-6.97 mmol nitrate m⁻² day⁻¹.

Keywords: Northern Gulf of Alaska shelf, nutrients, new production, chlorophyll *a*, annual cycle, interannual variability.

2.2 Introduction

The northern Gulf of Alaska (GOA) shelf is a very productive region insofar as it supports several commercially important fisheries such as salmon, halibut and pollock (Ware and McFarland, 1989). These fisheries are supported by phytoplankton production which is estimated to be as high as ~300 g C m⁻² y⁻¹ annually in shelf areas of the GOA (Sambrotto and Lorenzen, 1987). However, the mechanisms that support this high level of productivity are not understood. The northern GOA is a deep, coastal downwelling shelf fed by nitrate-poor runoff, which contrasts with the traditional highly productive upwelling regions, such as those along the eastern boundaries of the Pacific Ocean. Shelf regions along the eastern edge of the Pacific Ocean support productive ecosystems due to wind-driven upwelling, which regularly replenishes the euphotic zone with nutrients from deep, nutrient-rich waters. The GOA, on the other hand, only experiences episodic weak upwelling during the summer months when the cyclonic along-shore winds temporarily relax. Hence, during most of the year, the GOA is dominated by a downwelling circulation system (Royer, 1998).

Little work had been done on the distributions and concentrations of the major nutrients in the northern GOA shelf region prior to 1997. The sources and distributions of the major nutrients in this region, therefore, were previously unknown. The nutrient data reported here, which is part of the GOA Global Ocean Ecosystems Dynamics

(GLOBEC) Long Term Observation Program (LTOP), represent the first systematic record (1998-2000) of major nutrient concentrations across the GOA shelf. In this paper, the annual cycles and interannual variability of four major nutrients (nitrate, silicate, phosphate and ammonium) and chlorophyll *a* across the GOA shelf are examined. Estimated rates of new production are compared to other regions in the North Pacific.

2.3 Methods

2.3.1 Study area: The Gulf of Alaska

Two major surface flows exist over the northern GOA shelf (Fig. 2.1). The Alaska Coastal Current (ACC) is a narrow (<40 km), swift coastal current driven seasonally by coastal fresh water discharge and winds (Royer, 1981b). ACC transport reaches a maximum in late fall and early winter due to accumulated fresh water discharge and strong, cyclonic wind stress. A minimum occurs in early summer prior to the spring melt when the winds are weak. The Alaska Current/Alaskan Stream is a broad (100-400 km) current system that flows along the continental slope and is the northern limb of the subarctic cyclonic Alaska Gyre (Royer, 1981a).

The GOA shelf has a very complex bathymetry. In the northern Gulf, the continental shelf is relatively broad, (50-150 km), deep (150-250 m) and complicated by numerous ridge and trough features (Royer and Muench, 1977). Numerous silled and unsilled fjords, embayments, capes and island groups complicate the coastline (Reed and Schumacher, 1986). There are also submarine canyons that influence the bottom flows and potentially provide conduits between the inner and outer shelves.

The flows in the northern GOA are further complicated by eddy activity. There is increasing evidence of small, transient eddies that frequent the GOA shelf, in combination with very large, long-lasting eddies that travel along the continental slope for two to three years (Crawford and Whitney, 1999; Okkonen et al., 2002). These eddies likely influence the nutrient distributions by transporting and mixing the water column and could play a large role in supplying nutrients to the euphotic zone.

The annual shelf water properties in this region have two extremes, as described by Royer (1975). During winter, the intensification of cyclonic atmospheric circulation over the GOA produces easterly coastal winds and downwelling, both resulting in a well-mixed water column. During summer, stratification increases due to weak winds, freshwater discharge and solar insolation. Under summer and fall conditions, the shelf waters are stratified with the upper water column temperatures at their maximum and salinities at their minimum (Royer, 2005).

On longer time scales, there is evidence of interannual variation in GOA flows and properties. These variations result from the climatic variability of the El Niño/Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) (Royer, 2005). Throughout the twentieth century, PDO events, or phases, persisted for 20 to 30 years while ENSO events persisted 6 to 18 months (Mantua, 1999). ‘Warm’ phases of the PDO coincide with enhanced coastal ocean biological productivity in Alaskan waters and decreased productivity along the west coast of the United States (California, Oregon and Washington) (Hare et al., 1999). The opposite pattern emerges during ‘cool’ phases. It appears that the most recent ‘warm’ phase of the PDO lasted from 1977 through 1999, and has since entered into a ‘cool’ phase (NASA, 2003; Peterson and Schwing, 2003). There was also a very strong El Niño in 1997-1998, followed by a strong La Niña event in late 1998 and 1999 (NOAA, 2003). These phase changes of ENSO and PDO encompass the years the data reported here were collected and might account for a large degree of interannual variability found in the oceanographic properties of the northern GOA.

2.3.2 Data collection

The data discussed here were collected on eighteen cruises throughout 1998-2000 aboard the R.V. *Alpha Helix* as part of the Global Ocean Ecosystem Dynamics (GLOBEC) Gulf of Alaska Long Term Observation Program (LTOP). There were six cruises per year spanning all seasons (Table 2.1) along the Seward Line (Fig. 2.1). This cross-shelf transect encompasses both the shelf waters within the Alaska Coastal Current and the slope waters within the Alaskan Current/Stream.

Nutrient samples were collected at all stations along the Seward Line transect. Samples were taken every 10 m in the upper 50 m, and at varying intervals throughout the water column below 50 m, depending on bottom depth and the temperature, salinity, or fluorescence profiles. Samples collected in 1998 were frozen for later analysis in the laboratory of five macronutrients: nitrate, nitrite, silicate, phosphate and ammonium. Samples collected in 1999 and 2000 were analyzed aboard ship for the same macronutrients shortly after sampling. Experiments performed on fresh versus frozen samples confirmed that the freezing and thawing process, when done properly and carefully, did not alter nutrient concentrations. The chemical analyses of these nutrients were performed using colorimetric techniques on Technicon AutoAnalyzer II and Alpkem model 300 continuous nutrient analyzers (Whitledge et al. 1981). The samples were collected in association with temperature and conductivity measurements taken with a Sea Bird 911 Plus CTD/rosette sampler with twelve, five-liter Niskin bottles. A Wet Labs fluorometer attached to the CTD/rosette system provided chlorophyll *a* fluorescence profiles at each station. Discrete upper water column samples were also collected for *in vitro* chlorophyll *a* analysis. Chemical analyses and preparation of the samples are described in detail by Childers (2001).

Integrated chl *a* concentrations discussed and presented here were calculated by integrating the upper 50 m, which is the estimated average depth of the euphotic zone. This also allowed for direct comparisons among the chlorophyll data. When extracted chlorophyll was missing at some depths in the profile, chlorophyll concentrations were estimated from calibrated fluorescence profiles.

2.4 Results

The data collected from the Seward Line can be more easily described and compared by dividing this transect into four shelf regimes with representative stations (Fig. 2.1). 1) The inner shelf regime consists of the ACC, which varies in width, but is generally located within 35-50 km of the coast. This regime lies inshore of the ACC front and is heavily influenced by freshwater discharge and downwelling winds. 2) The

middle shelf regime lies between the inner shelf and shelf break, ~50-125 km from the coast. This portion of the shelf is characterized by variable flow associated with shelf eddies and ACC frontal dynamics. 3) The shelf break regime is influenced by the shelf-break front, ~135-160 km from the coast. Shelf-break frontal meanders, shears and onshore advection of slope waters affect this portion of the shelf. In addition, large eddies traveling in the GOA along the continental slope promote mixing and upwelling events (Okkonen et al., 2002). 4) The slope regime lies offshore of the shelf break over the continental slope and is within the Alaskan Current/Stream. The slope waters are influenced primarily by features including slope eddies and the Alaskan Current/Stream. GAK 1, GAK 4, GAK 9 and GAK 13 represent these four shelf regimes, respectively.

2.4.1 The annual cycle

2.4.1.1 The Seward Line

In this section, we discuss nutrient data from all three years (1998, 1999 and 2000), but for brevity show only selected 2000 occupations, whereas Fig. 2.3 shows all three years of chlorophyll data. The April and December nutrient and chlorophyll data are not presented as they were very similar to March and October, respectively.

In March (late winter, pre-bloom), the upper water column across the shelf and slope was well mixed with minimum temperatures and salinities over the inner shelf, within the ACC (3.1-4.9 °C, 30.5-31.7 psu) and maximum values offshore (5.3-6.5 °C, 32.5-32.8 psu) (Fig. 2.2). Nutrient concentrations in the upper 50 m ranged from 6.6-21.7 $\mu\text{M NO}_3^-$, 10.6-36.4 $\mu\text{M Si(OH)}_4$ and 0.5-2.3 $\mu\text{M PO}_4^{3-}$, with lower values inshore and higher values offshore. Salinity, nitrate, silicate and phosphate generally increased with depth and distance offshore reaching maximum values of 34.5 psu, 43-50 $\mu\text{M NO}_3^-$, 86-198 $\mu\text{M Si(OH)}_4$ and 2.9-3.6 $\mu\text{M PO}_4^{3-}$ offshore of the shelf break below the permanent halocline (defined as 200-250 m, 32.5 to 33.8 psu). Ammonium was always low (<1.0 μM) and uniformly distributed.

March chl *a* concentrations were low, $<0.84 \mu\text{g l}^{-1}$, with a mean of $0.24 \mu\text{g l}^{-1}$. Depth integrated chl *a* concentrations were $<35 \text{ mg m}^{-2}$ (mean = 12.8 mg m^{-2}) with increasing concentrations offshore in 1998 and 2000 (Fig. 2.3).

In May (spring bloom) the water column began to warm and stratify with surface temperatures between 4.8 and 7.8°C and salinities between 29.4 – 32.7 psu, with the lowest values inshore (Fig. 2.4). Nitrate concentrations in the upper ~ 20 m decreased slightly from those of March to $<17.4 \mu\text{M}$ with minimum values of $<4.0 \mu\text{M}$. Silicate concentrations in the upper ~ 50 m decreased from March to $<28.0 \mu\text{M}$ with concentrations $<5.0 \mu\text{M}$ occasionally measured in the upper 20 m. Phosphate concentrations also generally decreased to 0.4 – $1.7 \mu\text{M}$ in the upper 50 m. Ammonium concentrations were commonly $<1.0 \mu\text{M}$; however, there were regions where concentrations were greater (2.0 – $5.0 \mu\text{M}$). The shelf waters below ~ 100 m were more saline and enriched in nitrate, compared to March. These higher salinities (>33 psu) and nitrate concentrations ($>25 \mu\text{M}$) were associated with offshore waters that migrate inshore annually in summer.

The chl *a* concentrations in May showed a notable increase in chlorophyll across the shelf with a mean of $1.87 \mu\text{g l}^{-1}$ and integrated mean value of 99.9 mg m^{-2} . The higher concentrations occurred over the inner and middle shelves in 1998 and 2000 (Fig. 2.3). However, in May 1999, chlorophyll distributions were very patchy and exceptionally high over the outer shelf and slope with concentrations as high as $18.72 \mu\text{g l}^{-1}$ and 703.5 mg m^{-2} at GAK 10.

By July and August (summer), the water column was strongly stratified (Fig. 2.5a & 2.5b). Surface water temperatures were between 11.2 and 15.0°C . The surface salinities were low over the inner and middle shelves (<32.0 psu), with the lowest salinities along the coast within the ACC (24.1 – 25.2 psu) as a result of freshwater runoff. The surface waters (<10 m) across the shelf reached annual minimum concentrations of nitrate, silicate and phosphate ($<5.4 \mu\text{M}$, $<13.2 \mu\text{M}$ and $<0.7 \mu\text{M}$ respectively), with the lowest concentrations along the coast. Below this nutrient-poor layer, nutrient concentrations increased notably to values as high as $31.0 \mu\text{M NO}_3^-$, $26.3 \mu\text{M Si(OH)}_4$

and $1.75 \mu\text{M PO}_4^{-3}$ at 50 m. Ammonium concentrations were generally $<2.4 \mu\text{M}$; however, there was a patch of higher ammonium concentrations ($2.8\text{--}7.1 \mu\text{M}$) over the shelf break in August 1999. The deep shelf waters were more saline and enriched in nitrate, silicate and phosphate compared to May. The 33 psu isohaline now extended over the middle shelf onto the inner shelf to depths of 130–200 m. The maximum nutrient concentrations at depth over the inner shelf increased by $5\text{--}15 \mu\text{M NO}_3^-$, $8\text{--}34 \mu\text{M Si(OH)}_4$ and $0.3\text{--}1.8 \mu\text{M PO}_4^{-3}$.

The July/August chl *a* concentrations were lower than in May, but remained relatively high, with a mean of $0.95 \mu\text{g l}^{-1}$ and mean integrated value of 39.9 mg m^{-2} . The depth integrated chl *a* concentrations showed no apparent pattern across-shelf (Fig. 2.3). The highest chl *a* concentrations were between 10 and 25 m, either just above or within the summer pycnocline.

In October (fall), the water column was moderately stratified. The water column between 50–200 m was warmer than in July/August, with a thick surface layer (20–25 m) of warm water ($8.5\text{--}10.9^\circ\text{C}$) due to the onset of winter mixing (Fig. 2.6). The ACC was more clearly defined with salinities <31.5 psu extending to 50–80 m depth near the coast. The nitrate concentrations in the upper 10 m increased slightly since summer, while the concentrations between 10 and 50 m decreased presumably due to mixing of the upper water column. Silicate and phosphate concentrations in the upper 50 m generally increased from summer to fall. Ammonium concentrations were low ($<1.8 \mu\text{M}$) and uniform cross-shelf. Near bottom nutrient concentrations decreased from those of spring and summer. The 33 psu isohaline deepened over the inner and middle shelves due to re-establishment of downwelling.

October chl *a* concentrations were generally lower than summer (mean = $0.72 \mu\text{g l}^{-1}$ and integrated mean = 29.5 mg m^{-2}) (Fig. 2.3). In October 1998 and 1999, the integrated chl *a* concentrations were low ($<14.0 \text{ mg m}^{-2}$) and uniform across the transect; however, in October 2000, integrated chl *a* was higher than the previous two years and the previous summer concentrations with the highest concentration(s) ($7.90 \mu\text{g l}^{-1}$, 173.2 mg m^{-2}) over the inner shelf.

2.4.1.2 The four shelf regime stations

Across-shelf variability of the annual cycle is illustrated by forming the three-year averages of the physical and chemical distributions at the four stations (GAK 1, 4, 9 and 13) representative of each regime.

At station GAK 1, from the inner shelf, the water column was weakly salt-stratified in March and April, with surface stratification increasing in late April and May due to increasing freshwater discharge (Fig. 2.7). Freshwater discharge and solar heating further strengthened stratification through summer (surface = 25.6 psu and 14 °C). As the downwelling wind stress increased through fall, stratification eroded, although even in December the water column remained moderately stratified due to salinity. In addition to the large seasonal changes in near-surface stratification, there were pronounced changes in deep salinities. Salinities at depth were relatively low (~32.6 psu) in March and April when downwelling winds were strong, increased to 33.4 psu in summer as downwelling relaxed, and decreased through fall as downwelling increased.

The nutrient concentrations at GAK 1 were nearly uniform throughout the upper 100 m in March (mean = 13 μM NO_3^- , 23 μM Si(OH)_4 and 1.3 μM PO_4^{3-}) (Fig. 2.7). Nutrient drawdown was evident by April in the upper 50-100 m, suggesting consumption by phytoplankton. By summer, nitrate, silicate and phosphate concentrations in the upper 20 m were <1.4 μM , <5 μM and <0.5 μM , respectively. Nutrient depletion is commonly recognized to occur for phytoplankton when concentrations become less than twice the half-saturation constant (K_s), which is equal to the nutrient concentration at half the maximum growth rate (μ_{max}). We defined nutrient depletion using the following K_s values: 1-2 μM NO_3^- , 5 μM Si(OH)_4 and 0.5 μM PO_4^{3-} (Lalli and Parsons, 1993; MacIsaac, 1969). By this definition, the upper 20 m at GAK 1 were nitrate, silicate and phosphate depleted, and possibly limited, during the summer months. Below 50 m, nitrate, silicate and phosphate increased over the spring and summer months to maximum values (bottom values were: 33 μM , 56 μM and 2.8 μM respectively). In fall (October-December), nutrient concentrations became more homogeneous throughout the water column. Averaged ammonium concentrations were low throughout most of the year

(<1.7 μM), except in May and December when concentrations reached $\sim 3.0 \mu\text{M}$ (Fig. 2.7).

The annual cycles at GAK 4, 9 and 13 were similar to GAK 1, although there were notable differences. (Station GAK 13 was not sampled during the April 1998 or October 2000 cruises due to unfavorable weather conditions.) At these offshore stations, water column salinities increased while the annual range in salinity decreased compared to GAK 1 (Fig. 2.8, 2.9, & 2.10). At GAK 9 and 13, salinities and temperatures below the permanent halocline were relatively constant throughout the year; however, the enriched nutrient concentrations (23-50 $\mu\text{M NO}_3^-$, 39-134 $\mu\text{M Si(OH)}_4$, 1.7-4.1 $\mu\text{M PO}_4^{3-}$) were not steady throughout the year. March nutrient concentrations averaged over the upper 100 m at GAK 4, 9 and 13 were similar to those from GAK 1 ($\pm 3\text{-}4 \mu\text{M NO}_3^-$ and Si(OH)_4 and $\pm 0.1 \mu\text{M PO}_4^{3-}$). Over the spring months, drawdown of nitrate was not evident until May at these outer stations. By summer, nitrate, silicate and phosphate concentrations were depleted from the upper 10 m at GAK 4, while nitrate and phosphate were depleted from the upper 10 m at GAK 9 and 13 with silicate at the annual minimum (5.4-6.5 $\mu\text{M Si(OH)}_4$). At depths just below these minimum summer concentrations (25-50 m), nutrient concentrations generally increased compared to spring. Ammonium concentrations were generally low (<1.7 μM) throughout the year at the outer stations with only occasionally higher concentrations in July/August and December.

2.4.2 Interannual variability

The data collected from 1998-2000 include substantial interannual variability. This is most clearly shown in time series from the four shelf regime stations. Beginning in March, interannual variations in physical and chemical properties were similar at stations GAK 1, 4 and 9 (Fig. 2.11-2.13). In March 1998, the water column across the shelf was moderately stratified and relatively warm, whereas in March 1999, the upper 100 m was well mixed and saltier and cooler than in 1998. In March 2000, the water column was strongly stratified with comparatively fresh surface waters at GAK 1 and 4. March nutrient concentrations averaged over the water column were lowest in 1998 and highest in 2000 at the three shelf stations. Over the three years, nutrients increased from

9.5 to 16.3 $\mu\text{M NO}_3^-$ at GAK 1, from 12 to 19 $\mu\text{M NO}_3^-$ and 21 to 30 $\mu\text{M Si(OH)}_4$ at GAK 4 and from 6 to 23 $\mu\text{M NO}_3^-$, 16 to 40 $\mu\text{M Si(OH)}_4$ and 1.1 to 1.7 $\mu\text{M PO}_4^{3-}$ at GAK 9 (only NO_3^- data shown). Over the slope (GAK 13) temperature and salinity data showed that the upper water column in March and April was mixed down to ~100 m in 1999 but to <50 m in 1998 and 2000 (Fig. 2.14). The GAK 13 data also showed that the late winter conditions in the upper 100 m were increasingly salty, cool and enriched in nitrate, silicate and phosphate from 1998 through 2000 (only NO_3^- data shown).

Following the distinctive late winter/early spring physical and chemical conditions, interannual variability was evident in nutrient drawdown and phytoplankton chlorophyll biomass. Springtime nutrient drawdown at GAK 1 and 4 was most pronounced in April 2000 when maximum chl *a* concentrations were measured at GAK 1 (289 mg m^{-2}) and GAK 4 (178 mg m^{-2}) followed by relatively high chl *a* concentrations in May 2000. By summer 2000, nitrate was depleted from the upper 10 m at GAK 1 and 4 and was further reduced between 20-30 m depth by the fall bloom in October 2000. Further offshore, maximum chl *a* concentrations were measured in May 1999 at GAK 9 (206 mg m^{-2}) and GAK 13 (548 mg m^{-2}) when nutrients were reduced in the upper 30-50 m. Nutrient replenishment was evident in October 1999 at all four stations; however, nitrate concentrations remained low in the upper 20-50 m in October 1998 at the four stations and in October 2000 at GAK 1 and 4. By December, water column averaged nutrient concentrations were generally lowest in 1998 and highest in 2000 at the four shelf regime stations.

2.4.3 Nutrient-salinity relationships

The relationship between salinity and nutrients was examined to determine how strongly the physical and chemical properties were correlated. The relationship between temperature and nutrients was not examined since salinity exerts dominant control over density in the GOA (Royer and Muench, 1977). The coefficient of determination, r^2 , was calculated to determine the degree of linear association between nitrate, silicate and phosphate and salinity for each of the eighteen cruises (months), which were all significant to the 0.001 level. These relationships were examined using data from depths

greater than 75 m, so that the influence of upper ocean biological processes was minimized. The r^2 values calculated between nitrate and salinity from the monthly data ranged between 0.63 and 0.96 with a mean of 0.87 (Fig. 2.15). The monthly r^2 values between silicate and salinity ranged from 0.57 to 0.87 with a mean of 0.73. The monthly r^2 values between phosphate and salinity were more variable with values between 0.40 and 0.93, except for March 1998, which had an extremely low value of 0.16; thus the overall mean was 0.74. The April 1998, 1999 and 2000 nitrate-salinity relationships demonstrate this strong positive correlation between nutrients and salinity over the GOA shelf (Fig. 2.16).

A closer evaluation of the data revealed that the strongest relationship between the nutrients and salinity within the water column was at depths between 150 and 300 m, while the weakest relationships were at depths greater than 500 m. This suggests that the nutrient-rich waters beyond the shelf-break at depths between 150-300 m may be the primary nutrient source to the shelf. The occurrence of relatively weak relationships at depths shallower and deeper than 150-300 m suggest biological effects extend deeper than 75 m and that there are multiple nutrient source waters.

Generally, the relationships were weaker in 1998 and stronger in 1999 and 2000. This difference could be due to the processing of frozen samples. Since the samples in 1998 were processed after being frozen and transported, while the samples in 1999 and 2000 were run within hours of collection, a sampling error may have been introduced. However, we have no evidence that the frozen samples were in error, so this distinction could be due to interannual differences between 1998, 1999 and 2000, which were also evident in the temperature and salinity profiles.

Overall, since there is a strong relationship between nutrients and salinity over the GOA shelf, salinity can be used as a proxy for nutrient concentrations from historical salinity data or for future monitoring. Also, since large concentrations of regenerated forms of nutrients were not commonly found, either in the mixed layer or subpycnocline layer, nutrient remineralization is probably a secondary source of nutrients supporting productivity.

2.4.4 New production estimates

First order estimates of new production were calculated from the mean depth integrated nitrate concentrations (0-50 m) within the four shelf regimes for the time periods March-April, April-May and May-July/August 1998, 1999 and 2000 (Table 2.2). These calculations assume that March and July/August represented annual maximum and minimum nitrate concentrations and ignore the effects of nutrient advection and diffusion and other gains and losses in the upper 50 m. These estimates are therefore conservative because these processes cannot be estimated with the existing data. Negative values are not shown since they imply that nitrate supply exceeded nitrate utilization.

Throughout the three years, estimates of daily new production averaged over the spring-summer season from the four shelf regimes ranged from 2.46 to 6.97 mmol nitrate $\text{m}^{-2} \text{day}^{-1}$. Within each spring-summer season, the greatest rates were found over the middle shelf in 1998 (6.60 mmol nitrate $\text{m}^{-2} \text{day}^{-1}$), over the shelf break in 1999 (6.97 mmol nitrate $\text{m}^{-2} \text{day}^{-1}$) and over the middle shelf in 2000, which was the overall greatest new production rate (17.03 mmol nitrate $\text{m}^{-2} \text{day}^{-1}$). New production rates were generally higher in the spring, especially from April to May, than during the summer months. Inner shelf new production rates were greatest from March to April in each of the years. In contrast, shelf break new production estimates were consistently greatest from April to May.

2.5 Discussion

2.5.1 The annual cycle

The euphotic zone over the northern GOA shelf underwent an annual cycle that was evident in the physical, chemical and biological properties. Beginning in March when incident solar radiation was low, the water column was well mixed and the phytoplankton chlorophyll biomass was low (Fig. 2.2 & 2.3). Consequently, nitrate, silicate and phosphate concentrations in the upper water column were at their maximum concentrations due to winter mixing and little consumption by phytoplankton. In late April and May, the water column across the shelf was more stratified due to solar heating

and increasing freshwater discharge (Fig. 2.4). In response, the phytoplankton bloomed, reaching annually high chl *a* concentrations while reducing nutrient concentrations in the upper water column. By summer, the upper water column was strongly stratified with a nutrient-poor euphotic zone (Fig. 2.5a & 2.5b). The nutrient concentrations in the upper 10-20 m were depleted or near depletion due to phytoplankton consumption and reduced mixing. Nevertheless, relatively high nutrient concentrations were available beneath the summer pycnocline, which might episodically replenish surface layer nutrients. Summer phytoplankton chlorophyll biomass was relatively high and appeared concentrated in or just above the pycnocline, where both light and nutrients were available. In October, the stability of the water column weakened due to increased wind mixing (Fig. 2.6). Phytoplankton chlorophyll biomass generally decreased in the fall (except in 2000) in response to less sunlight, lower temperatures and greater mixing of the water column.

Nutrient concentrations at depth across the shelf also demonstrated an annual cycle. In late spring, enriched nutrient concentrations below 100 m extended across the entire shelf as the downwelling winds relaxed allowing the deep, saline, nutrient-rich slope waters to migrate onto the shelf. By summer, the deep nutrient concentrations, especially nitrate, were maximal, as were deep water salinities, presumably in response to the onshore flux produced by the reduction in along-shelf transport associated with relaxing downwelling winds (Chapman, 2000; Weingartner et al., 2005). This summer onshore flux established a nutrient enriched bottom layer over the inner and middle shelves that, to some extent, was subsequently mixed throughout the water column by winter winds. This annual two-step process, onshore nutrient flux at depth in summer, followed by winter mixing into surface layers, is likely important in supplying the nutrients that support primary productivity over the GOA shelf. Over the slope, large fluctuations in the nutrient concentrations below the permanent halocline indicate the water masses moving along the continental slope have different origins and are not static.

Spatial variability in the timing, duration and extent of nutrient drawdown was evident across-shelf. Nutrient drawdown appeared earlier in the spring over the inner shelf compared to the outer shelf and slope regimes, with these differences presumably

relating to differences in the timing of stratification across-shelf (Weingartner et al., 2005). By summer, nitrate, silicate and phosphate were all depleted from the upper 20 m over the inner shelf, while nitrate and phosphate were depleted from the upper 10 m and silicate was at the annual minimum over the outer shelf and slope. By fall, surface nutrient concentrations were being replenished over the outer portion of the shelf and slope; however, relatively low nutrient concentrations remained over the inner shelf. The earlier initiation, more extensive and longer duration of nutrient drawdown over the inner shelf was most likely due to freshwater discharge that greatly enhanced water column stratification.

2.5.2 Interannual variability

Data from the Seward Line stations showed that there was interannual variability across the northern GOA shelf, which was especially evident in the late winter conditions (Table 2.3). A large degree of interannual variability measured during these three years was due to the climatic phases of ENSO and PDO, which similarly affected the subarctic Pacific. In late winter 1998 (El Niño), the water column was relatively warm, fresh and stratified due to anomalously high freshwater discharge (Weingartner et al., 2005). These conditions resulted in relatively low nutrient concentrations across-shelf in 1998. Whitney and Welch (2002) also measured anomalously warm ocean temperatures and low winter nitrate levels in 1998 along Line P in the subarctic Pacific.

In late winter 1999 (La Niña), the northern GOA shelf was weakly stratified due to anomalously low freshwater discharge. Consequently, the water column was cooler, more saline and higher in nutrient concentrations than the previous spring. Whitney and Welch (2002) likewise measured cooler and more saline waters in 1999 compared to 1998 along Line P, with nitrate and silicate concentrations higher in 1999 by 2-3 μM and 4-7 μM respectively. Whitney and Welch (2002) further noted that conditions changed dramatically during the 1999 La Niña, when winter-spring ocean-mixed layer depths were 20-40 m deeper compared to 1997-1998. Correspondingly, the mixed layer depth was deeper by 30-50 m over the GOA shelf and slope in 1999 compared to 1998 (Weingartner et al., 2005).

In the winter and early spring of 2000, the northern North Pacific was 'recovering' from the strong La Nina event in 1998/1999 and might have begun to shift into a 'cool' phase of the PDO. The water column in the northern GOA in late winter was strongly stratified due to above normal freshwater discharge and relatively weak downwelling winds. Nutrient concentrations across the shelf and slope were generally greater in spring 2000 compared to spring 1998 and 1999.

Over the slope, late winter conditions in the upper water column were increasingly more saline, cooler and enriched in nutrients throughout the three years. This may indicate more upwelling in the GOA gyre and/or progressively stronger mixing of the upper water column during these three years.

These three late winter/pre-spring seasons, which developed in response to climatic variability, presented a variety of physical conditions over the northern GOA to which the phytoplankton community responded. In the spring of 1998, although nutrient concentrations were relatively low, phytoplankton chlorophyll biomass over the inner and middle shelves was two and three times higher than in spring 1999. The highest springtime chlorophyll of the three years occurred on the outer shelf and offshore of the shelf break in May 1999. This was probably due to upwelling associated with the trailing flank of an anticyclonic eddy traveling along the shelf break (Okkonen et al., 2002) rather than local shelf conditions. Overall, spring phytoplankton chlorophyll biomass over the inner and middle shelves was highest in 2000 and lowest in 1999. The combination of high nutrient concentrations and a stratified water column in the spring of 2000 might have been optimal for the phytoplankton community. Phytoplankton chlorophyll biomass indicated that stratification over the shelf and slope eddies were key environmental factors that enhanced primary productivity in this region of the GOA.

We also observed interannual variability across the shelf in summer and fall. Nutrients in the euphotic zone continued to be utilized faster than they were replenished in the fall of 1998 across the shelf and in the fall of 2000 across the inner and middle shelves. On the other hand, nutrients were replenished to the surface waters across-shelf in fall 1999, indicating that either enrichment processes had increased or biological

uptake had decreased allowing replenishment in 1999. In fall 2000, there was a notable phytoplankton bloom that extended across the shelf, although it was most apparent over the inner and middle shelves. December nutrient concentrations averaged throughout the water column were lowest in 1998 and highest in 2000, which was the same trend measured in late winter. Throughout the three years studied, nitrate, silicate and chlorophyll were greatest across the shelf in 2000, while chlorophyll over the outer shelf and slope was greatest in 1999 during the presence of an eddy.

2.5.3 New production

Estimates of new production rates were first order approximations derived from changes in upper water column nitrate concentrations over the spring and summer months. It needs to be emphasized that these calculations are underestimations of new production rates since there were obviously periods throughout the spring and summer months when nitrate supply exceeded utilization even when phytoplankton growth was greatest. These estimates show that new production rates were intermittently high over monthly periods throughout the spring and summer. New production rates were highest over the inner shelf in early spring each of the three years. This was most likely due to earlier stratification of the euphotic zone over the inner shelf by freshwater inputs. Farther offshore, over the outer shelf and slope, rates were generally higher later in the spring, from April to May, most likely due to later stratification of the water column. The regime with the highest rates of new production rates changed from year to year demonstrating the degree of variability across this shelf.

These new production estimates from the northern GOA shelf are overall higher than estimates from Ocean Station Papa (OSP) in the subarctic North Pacific (Wheeler, 1993; Wong et al., 2002). Wheeler (1993) calculated rates of nitrate depletion in the upper 80 m of the water column at OSP that averaged $12 \text{ mg nitrate-N m}^{-2} \text{ day}^{-1}$ ($0.86 \text{ mmol nitrate m}^{-2} \text{ day}^{-1}$), with the highest rates in May, $\sim 75 \text{ mg nitrate-N m}^{-2} \text{ day}^{-1}$ ($\sim 5.36 \text{ mmol nitrate m}^{-2} \text{ day}^{-1}$). New production rates from the northern GOA shelf over the spring months were 2 to 3 times higher. Varela and Harrison (1999) found primary productivity along Line P was based on regenerated nitrogen (ammonium) with an *f*-ratio

of 0.21. The subarctic North Pacific is a high nitrate low chlorophyll region (HNLC) that has consistently low phytoplankton chlorophyll biomass that varies little seasonally (Harrison et al, 1999). Therefore, the subarctic North Pacific is clearly a very different ecosystem than the northern GOA shelf, which experiences nutrient depletion and phytoplankton blooms. However, the extensive research from Line P and OSP is the only existing data from the subarctic North Pacific that provides a regional comparison.

Wong et al. (2002) measured new production throughout the northern North Pacific during the years 1995-2000 and found similar trends with respect to interannual variability. Seasonal new production estimates from the Alaska Gyre and the Subarctic Current System were low from 1995 through 1999 then increased in 2000 to record high rates. This increase in 2000 was associated with high silicate depletions in the Alaska Gyre, indicating increased diatom production. Their study also found a large increase in new production during the 1997/1998 El Nino in the coastal regions surrounding the Alaska Peninsula (in the Alaskan Stream south of the Aleutian Islands) due to exceptionally rapid nitrate depletion. New production estimates from the northern GOA were also relatively high over the inner shelf in 1998.

2.5.4 Future directions

The source and movement of the major nutrients onto the shelf are not yet completely understood. However, the physical, chemical and biological data collected from nearby transects and additional years of data will help to clarify the features and dynamics within this region of the northern GOA shelf. For instance, the significance of transport of nutrient-rich slope waters through submarine features, such as Hinchinbrook Canyon and Amatouli Trough, to the shelf remains uncertain. It is also unknown if the waters flowing out of Prince William Sound influence the nutrient distributions over the inner shelf or if they export phytoplankton chlorophyll biomass onto the shelf. With the continued support of the Global Ocean Ecosystem Dynamics (GLOBEC) Gulf of Alaska Long Term Observation Program (LTOP), we will have an additional four years of data to analyze. We expect to better describe the annual nutrient trends across the shelf,

improving our understanding of the nutrient sources and dynamics that support this biologically productive shelf ecosystem.

The dynamics over the GOA shelf may potentially influence those over the southeastern Bering Sea shelf since the Alaska Coastal Current (ACC) connects these two shelves. The ACC flows along the GOA coastline then through the Aleutian Island passes onto the southeastern Bering Sea shelf. A closer examination of this connection between these two very productive shelves could potentially provide some direction for future research. Furthermore, the present basic understanding of the physical dynamics over the GOA shelf indicates that they may be similar to those over the southeastern Bering Sea shelf. For instance, both shelves experience a seasonal increase in salinity and nutrients in the bottom waters in mid to late summer, which are subsequently mixed throughout the water column by fall and winter mixing events (Whitledge et al. 1986; Stabeno et al., 2002). These two very productive shelf ecosystems are clearly connected by the ACC and driven by similar physical mechanisms. Therefore, this relationship should be the focus of future research.

Whitney and Welch (2002) speculate that the 1998 El Nino conditions potentially demonstrate the impacts of future global warming on the GOA. If so, warmer temperatures would increase stratification in the southern GOA and reduce nutrient supply to the euphotic zone (see Royer, 2005). This would result in less primary production in the southern region of the GOA. Conversely, warmer temperatures and increased freshwater discharge would increase stratification and potentially enhance primary productivity in the northern GOA. Nevertheless, the overall impact of global warming on the GOA is uncertain and will require much more research.

2.6 Conclusions

The northern Gulf of Alaska shelf is a dynamic shelf that supports an especially biologically productive ecosystem. However, since this shelf is dominated by persistent downwelling winds, the mechanisms supporting such high productivity were unclear.

These first three years of data provide a basic understanding of the nutrient distributions and dynamics across the GOA shelf as a result of physical features and biological uptake.

- The euphotic zone undergoes an annual cycle of nutrient drawdown and replenishment in response to the local physical dynamics and phytoplankton activity. During the spring and summer, nutrient concentrations in the upper water column were reduced to limiting or near limiting conditions by seasonally high phytoplankton chlorophyll biomass. In the fall and winter, wind mixing replenished the surface waters by distributing the higher nutrient concentrations from depth throughout the water column. Spatial variability in the timing, duration and extent of nutrient drawdown was evident along the Seward Line with surface nutrient drawdown over the inner shelf being the most extreme.
- Deep, nutrient-rich slope waters migrated onto the inner and middle shelves during the summer months, when downwelling was weakest. This onshore flux delivered dense, nutrient-rich water to the relatively deep inner and middle shelves, which remained until winter. Then during the winter months, the nutrient reservoir was mixed throughout the water column by winds and thermohaline processes, thereby supplying nutrients to the upper water column. This annual evolution may be crucial to biological production over this region of the northern GOA shelf. Furthermore, onshore Ekman transport in winter could also be a means by which nutrients are re-supplied to the shelf.
- The three years studied, 1998, 1999 and 2000, showed large degrees of interannual variability in the physical, chemical and biological distributions throughout the subarctic Pacific as these years were embedded within different phases of ENSO and the PDO (Mantua, 1999; NOAA, 2003).
- The passage of a slope eddy in the spring of 1999 demonstrated that these phenomena greatly enhance productivity over and beyond the shelf break and introduce a significant source of interannual variability.
- Estimated spring and summer new production rates were intermittently high temporally and spatially demonstrating the degree of variability across this shelf.

2.7 Acknowledgments

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Table 2.1 Seward Line occupations throughout 1998, 1999, and 2000.

1998	1999	2000
8-14 March	15-18 March	6-10 March
1-5 April	12-15 April	18-25 April
7-12 May	6-9 May	17-19 May
10-13 July	27-29 August	13-17 August
3-9 October	6-8 October	2-9 October
2-4 December	2-4 December	1-2 December

Table 2.2 New production estimates calculated from changes in 0-50 m integrated nitrate concentrations within the four shelf regimes during the March-April, April-May, May-July/August time periods in 1998, 1999, and 2000. Units are mmol nitrate m⁻² day⁻¹.

	March-April	April-May	May-Jul/Aug	Seasonal (# of days)
1998	(24 days)	(37 days)	(62 days)	
Inner shelf	9.14		2.70	5.92 (86)
Middle shelf	0.42		8.99	4.70 (86)
Shelf break		3.28	1.97	2.63 (99)
Slope		4.77	2.32	3.54 (99)
1999	(27 days)	(24 days)	(113 days)	
Inner shelf	5.95		2.00	3.97 (140)
Middle shelf	3.58		2.32	2.95 (140)
Shelf break	3.41	10.97		7.19 (51)
Slope	0.47	8.89		4.68 (51)
2000	(43 days)	(28 days)	(89 days)	
Inner shelf	4.58	3.08	2.30	3.32 (160)
Middle shelf		17.03		17.03 (28)*
Shelf break		12.17	0.06	6.11 (117)
Slope	2.00	0.43	4.00	2.14 (160)

*April-May only

Table 2.3 A summary of physical conditions, March nitrate concentrations, and phytoplankton biomass in the spring of 1998, 1999, and 2000.

	Downwelling Winds	Freshwater Discharge	Stratification	March [NO ₃ ⁻]	Phytoplankton Biomass
1998 (El Niño)	Strong	High	Strong	Lowest	
1999 (La Niña)	Average	Low	Weak		Highest (slope)
2000	Weak	High	Strong	Highest	Highest (shelf)

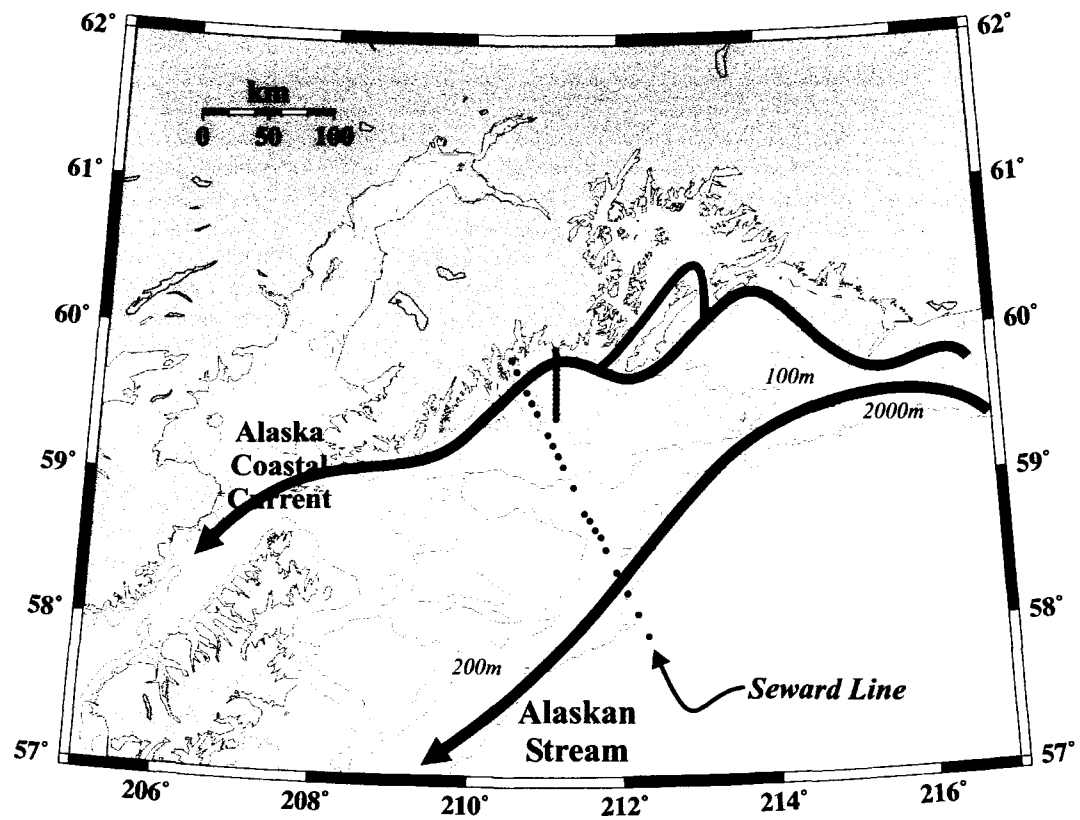


Figure 2.1 Gulf of Alaska surface currents: the Alaska Coastal Current (ACC) and the Alaska Current/Stream and the GLOBEC Seward Line with labeled stations: GAK 1, GAK 4, GAK 9 and GAK 13.

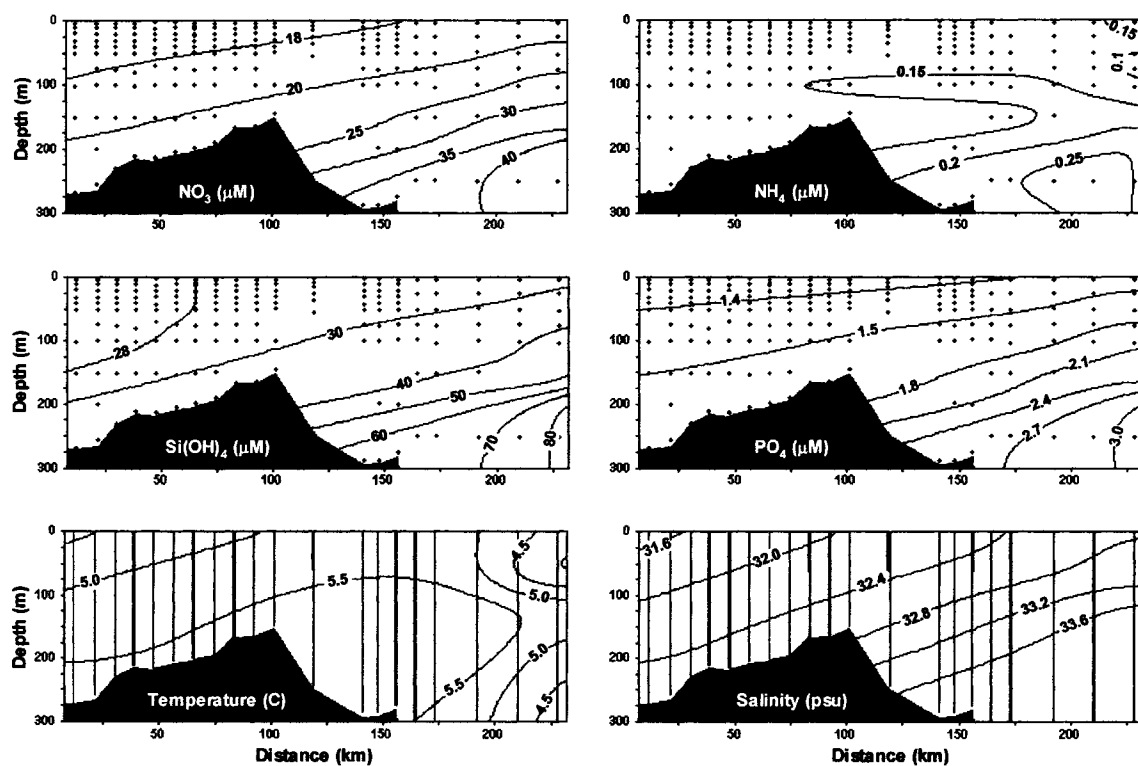


Figure 2.2 Vertical profiles of nitrate, ammonium, silicate, phosphate, temperature and salinity across the Seward Line taken 6-10 March 2000. Units are μM for nutrients, $^{\circ}\text{C}$ and psu (practical salinity units).

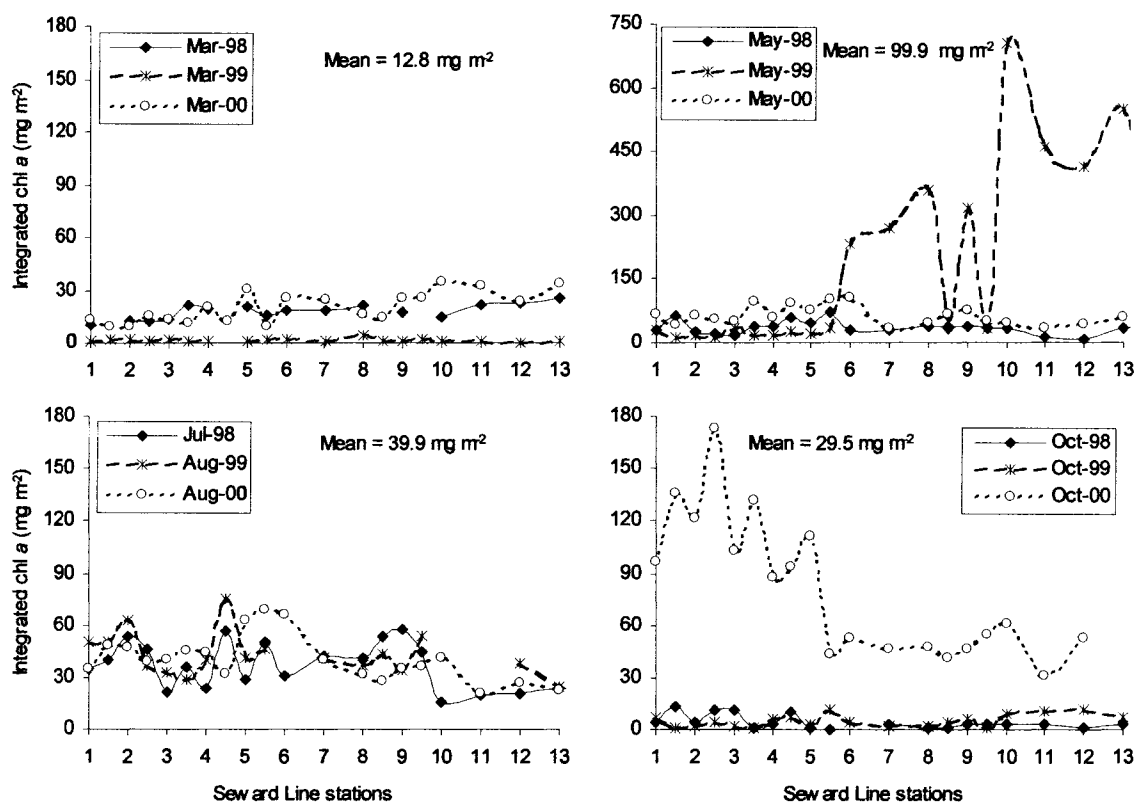


Figure 2.3 Integrated chl *a* concentrations (mg m⁻²) across the Seward Line in March, May, July/August and October 1998, 1999 and 2000. Note change of y-scale for May.

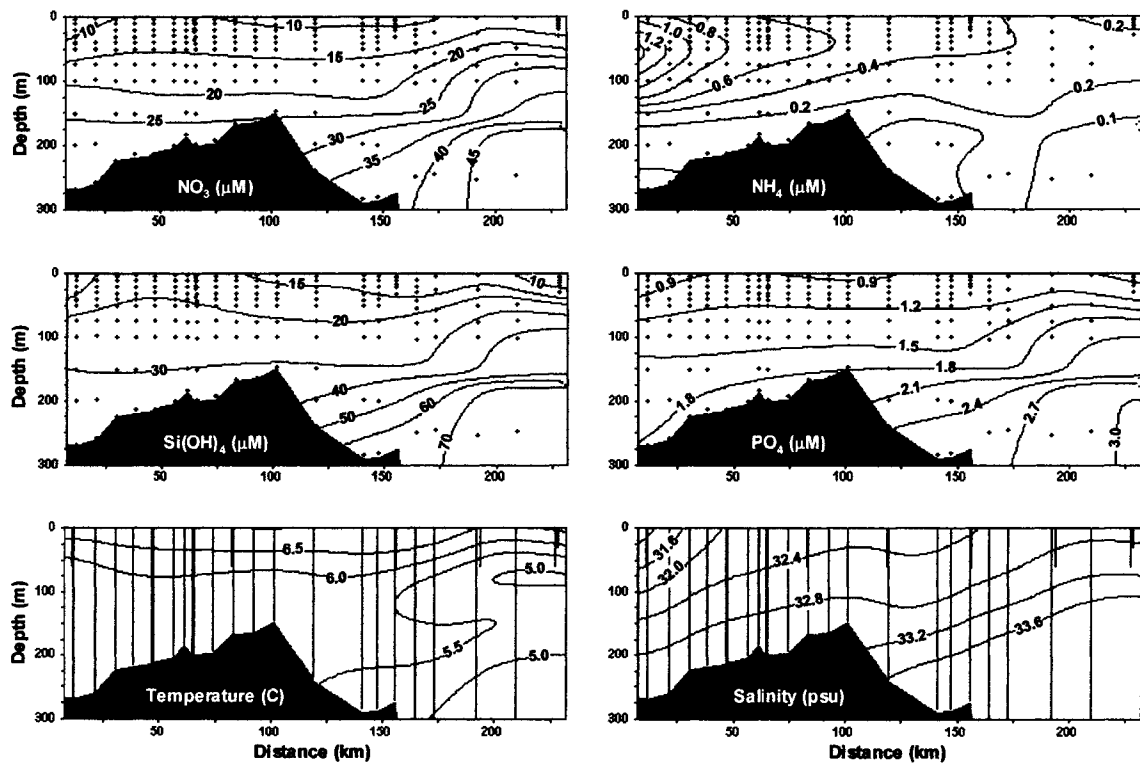


Figure 2.4 Vertical profiles of nitrate, ammonium, silicate, phosphate, temperature and salinity across the Seward Line taken 17-19 May 2000. Units are μM for nutrients, $^{\circ}\text{C}$ and psu (practical salinity units).

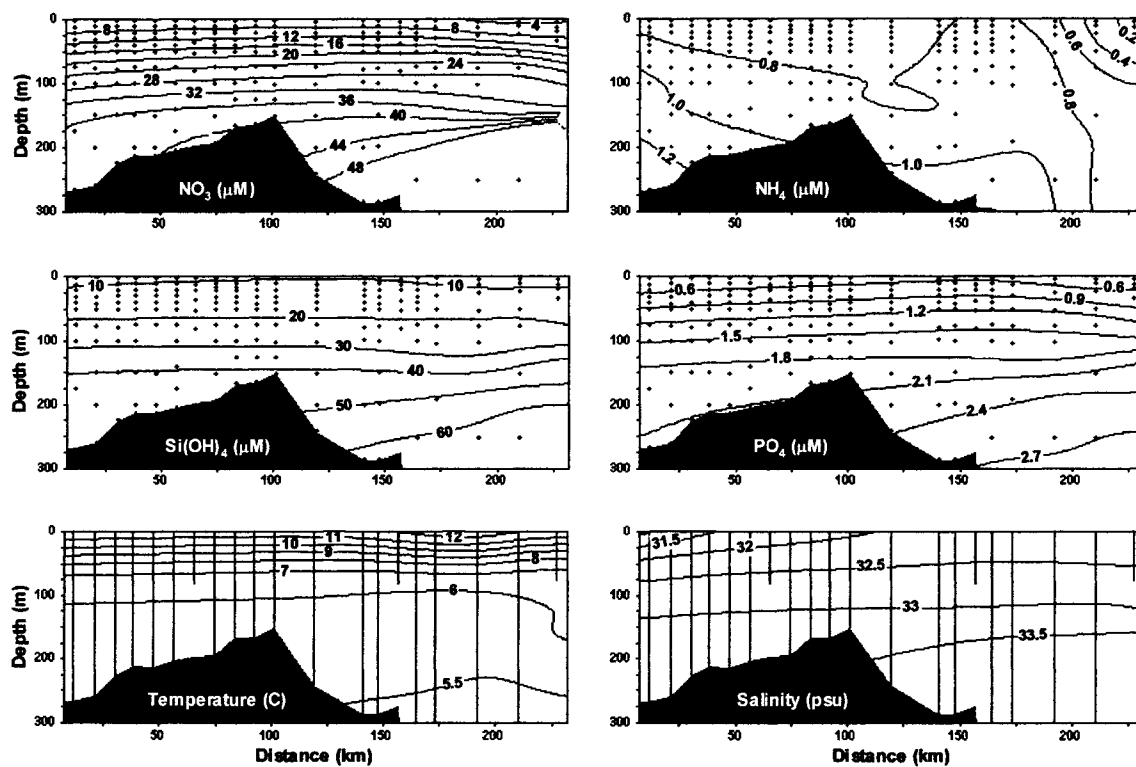


Figure 2.5a Vertical profiles of nitrate, ammonium, silicate, phosphate, temperature and salinity across the Seward Line taken 13-17 August 2000. Units are μM for nutrients, $^{\circ}\text{C}$ and psu (practical salinity units).

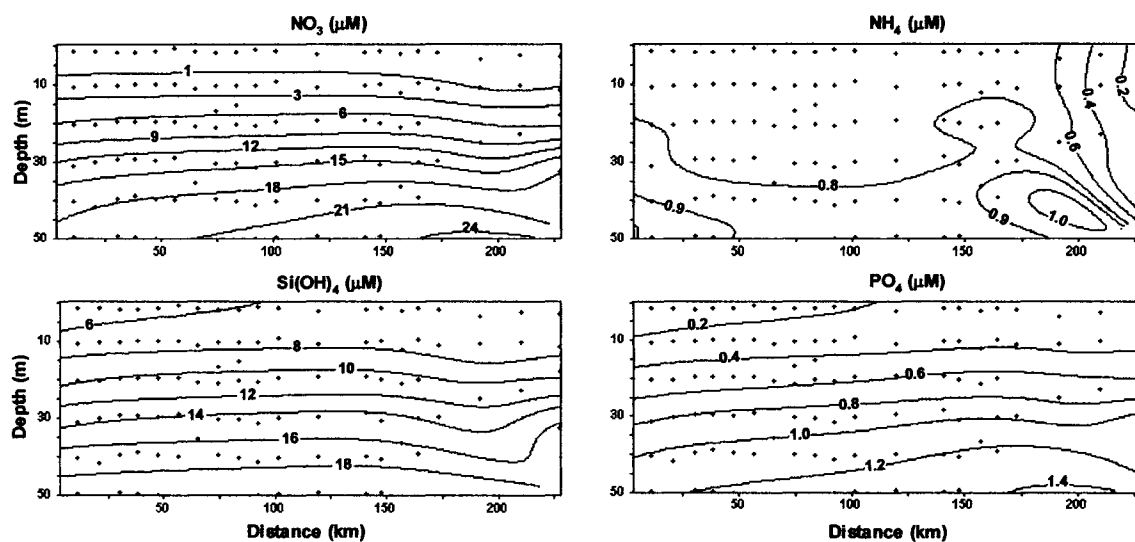


Figure 2.5b Vertical profiles of nitrate, ammonium, silicate, phosphate across the upper 50 m of the Seward Line taken 13-17 August 2000. Units are μM for nutrients.

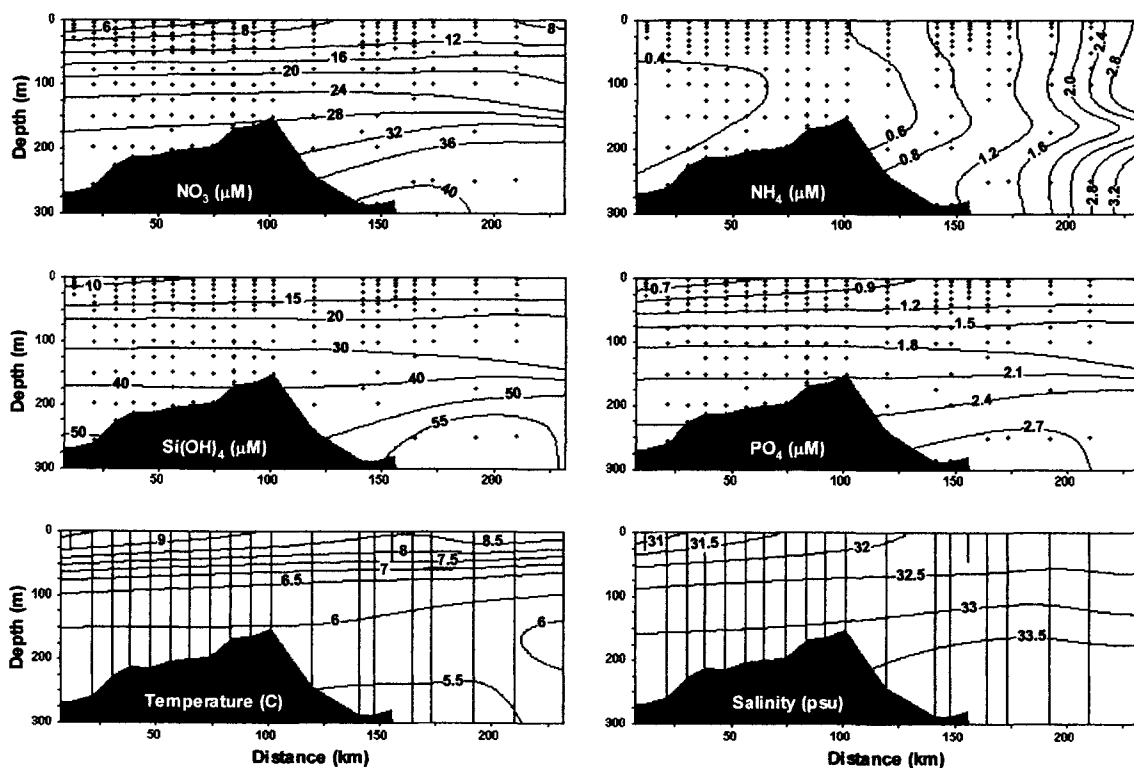


Figure 2.6 Vertical profiles of nitrate, ammonium, silicate, phosphate, temperature and salinity across the Seward Line taken 2-9 October 2000. Units are μM for nutrients, $^{\circ}\text{C}$ and psu (practical salinity units).

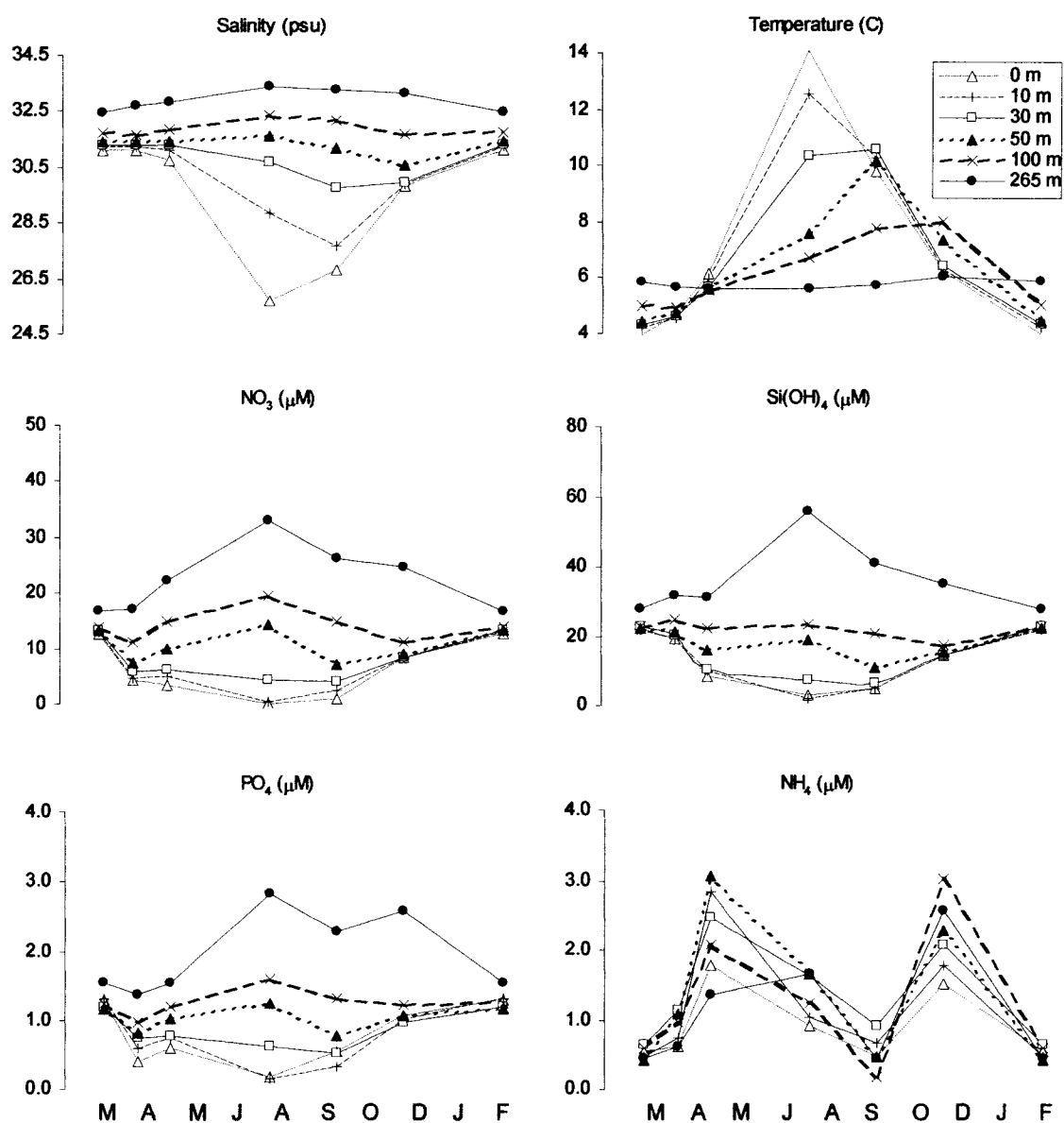


Figure 2.7 Averaged annual cycle of salinity, temperature, nitrate, silicate, phosphate and ammonium at GAK 1.

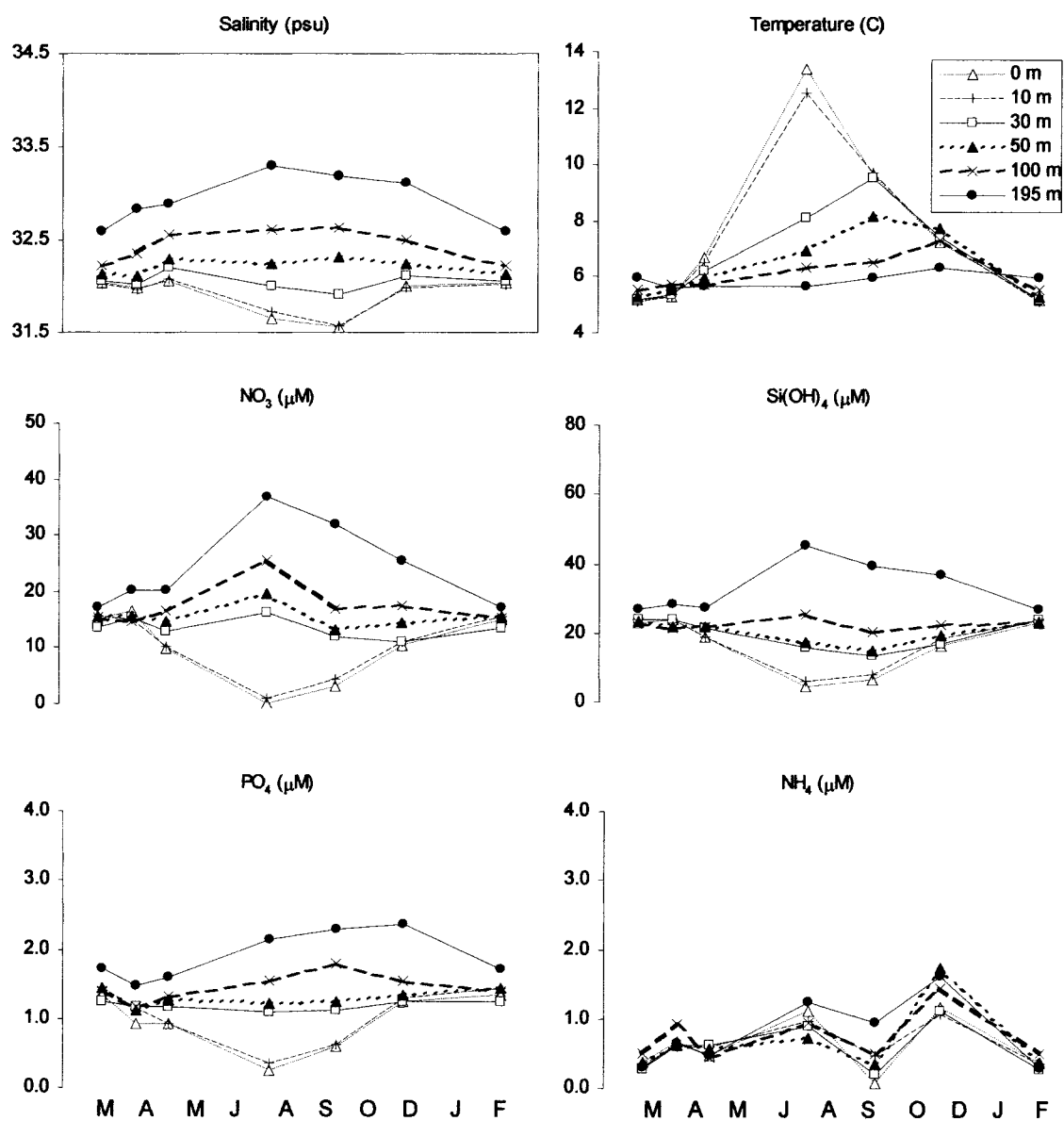


Figure 2.8 Averaged annual cycle of salinity, temperature, nitrate, silicate, phosphate and ammonium at GAK 4.

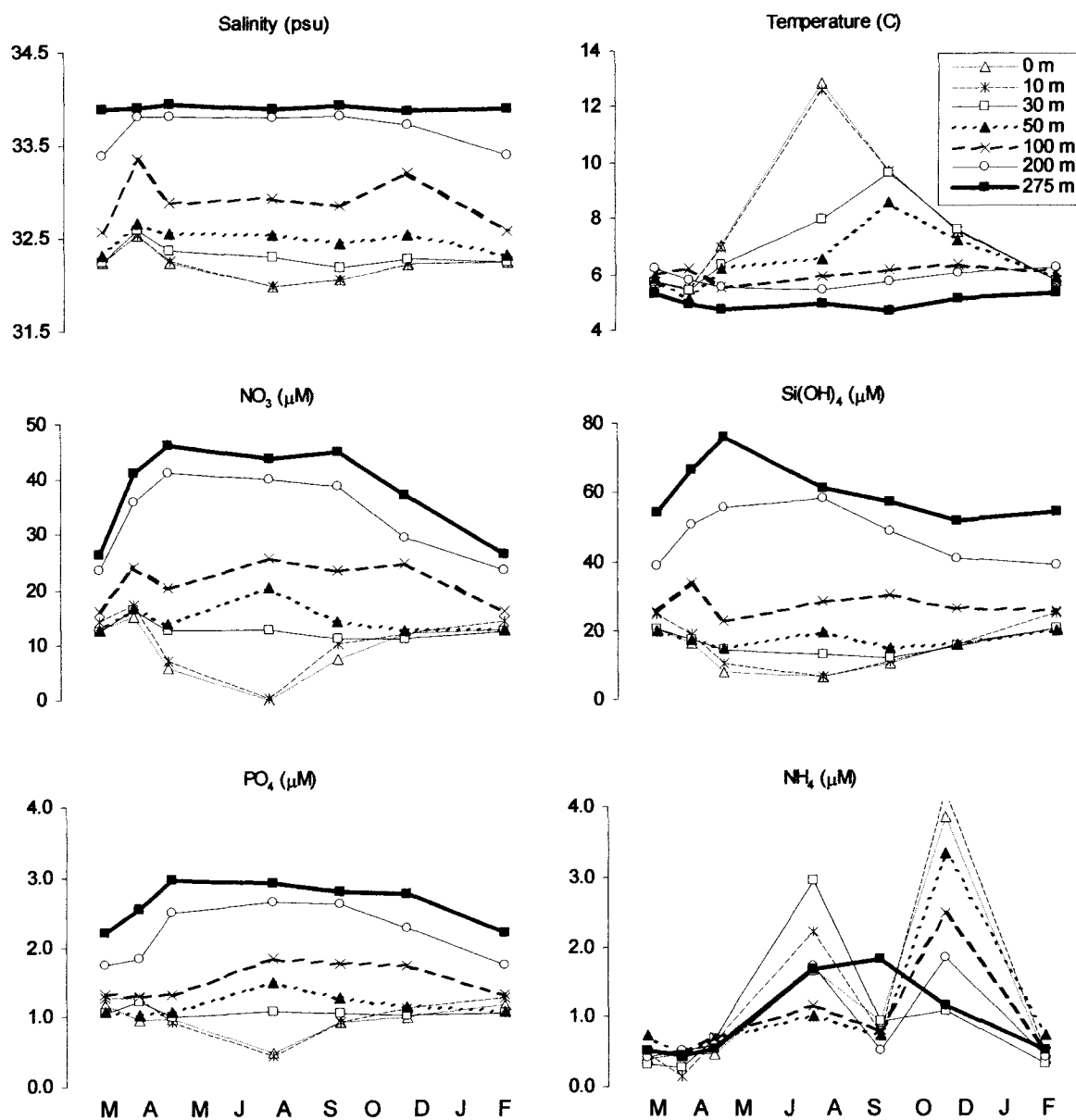


Figure 2.9 Averaged annual cycle of salinity, temperature, nitrate, silicate, phosphate and ammonium at GAK 9.

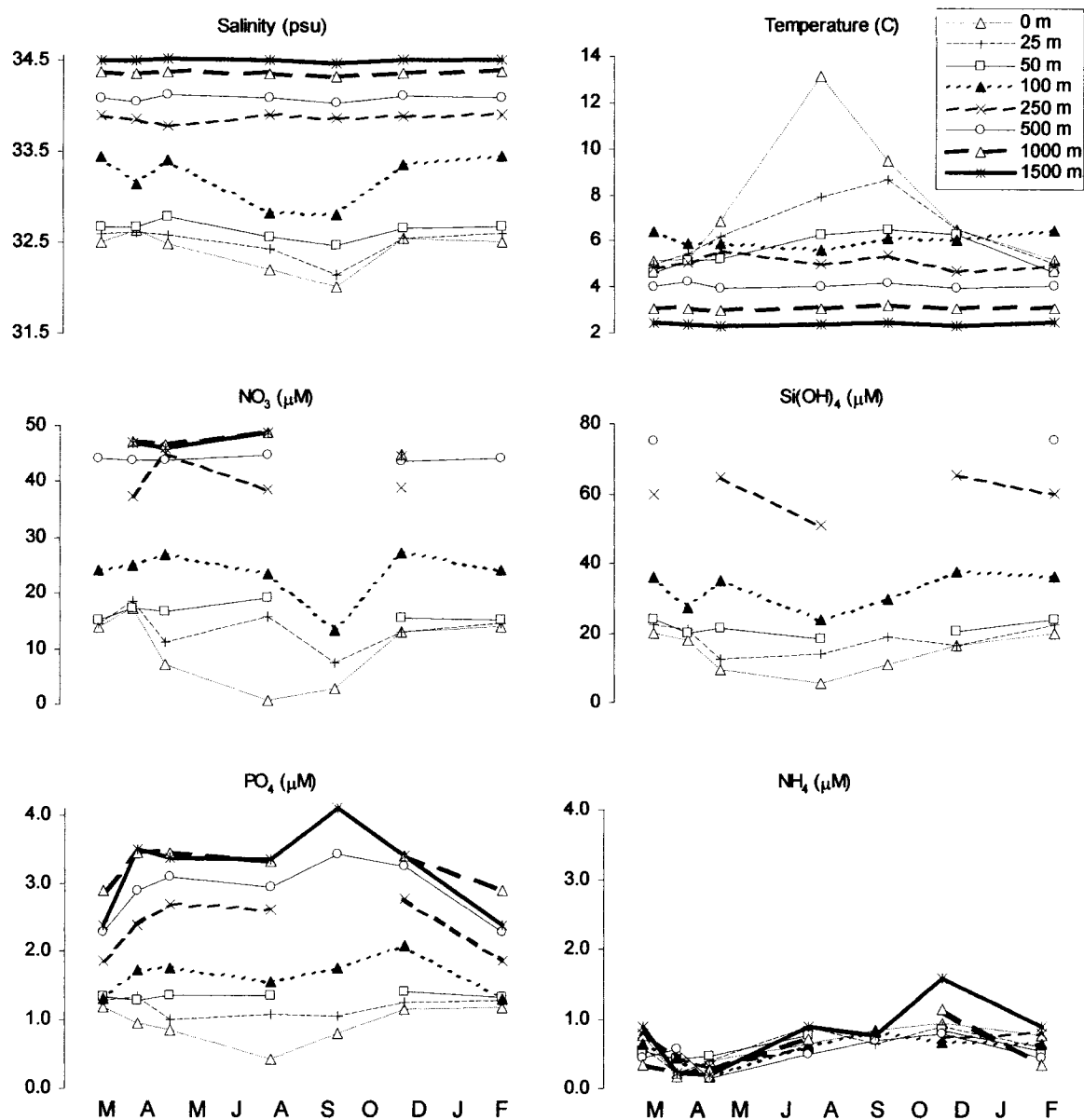


Figure 2.10 Averaged annual cycle of salinity, temperature, nitrate, silicate, phosphate and ammonium at GAK 13.

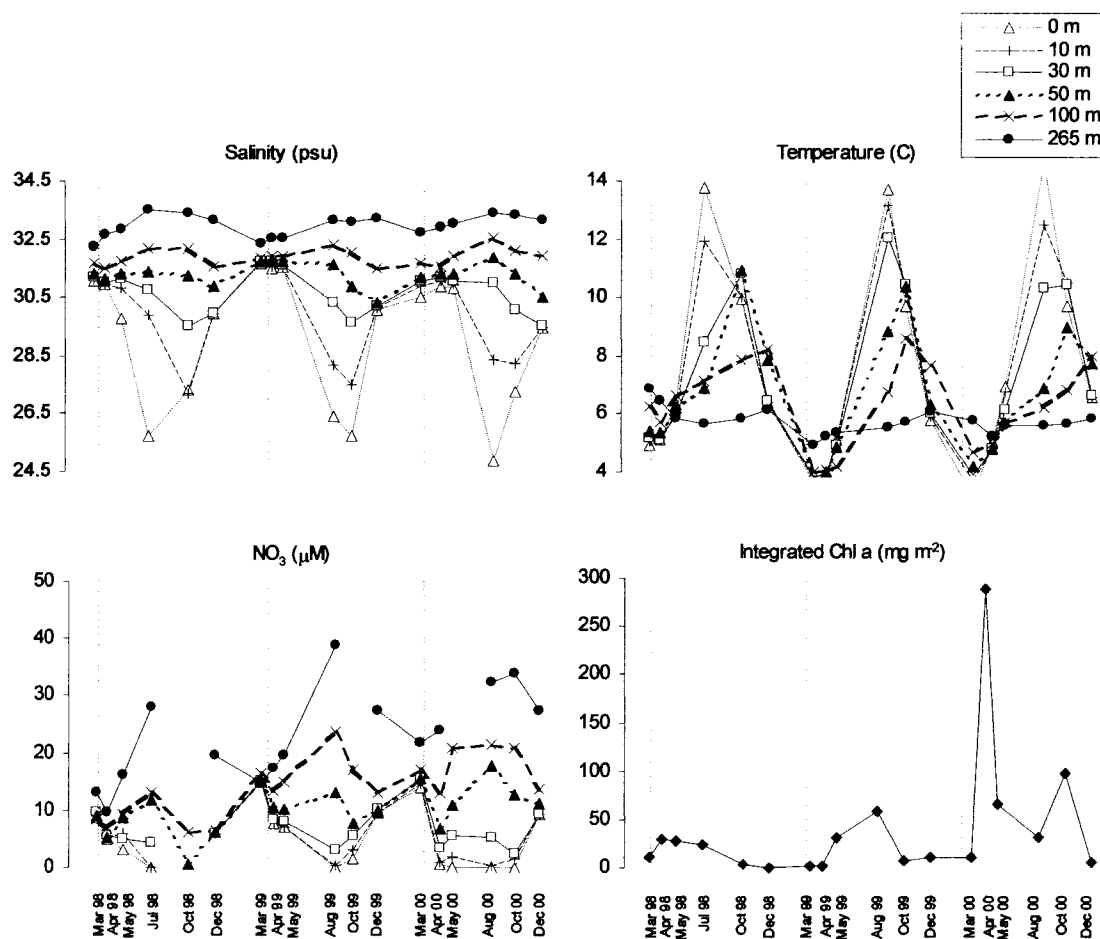


Figure 2.11 Time series at GAK 1 of salinity, temperature, nitrate and integrated chlorophyll *a* concentrations (0-50 m) March 1998 – December 2000. Dashed lines indicate March data.

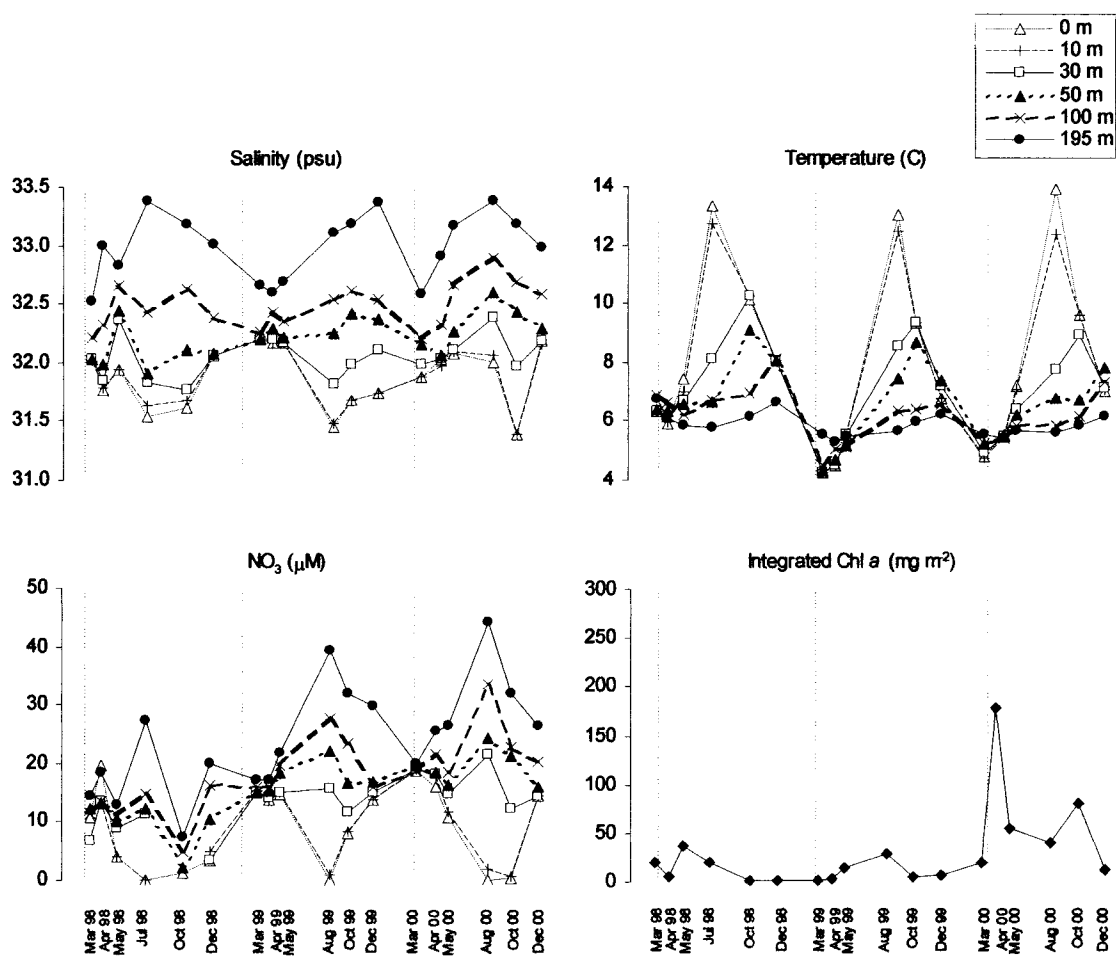


Figure 2.12 Time series at GAK 4 of salinity, temperature, nitrate and integrated chlorophyll *a* concentrations (0-50 m) March 1998 – December 2000. Dashed lines indicate March data.

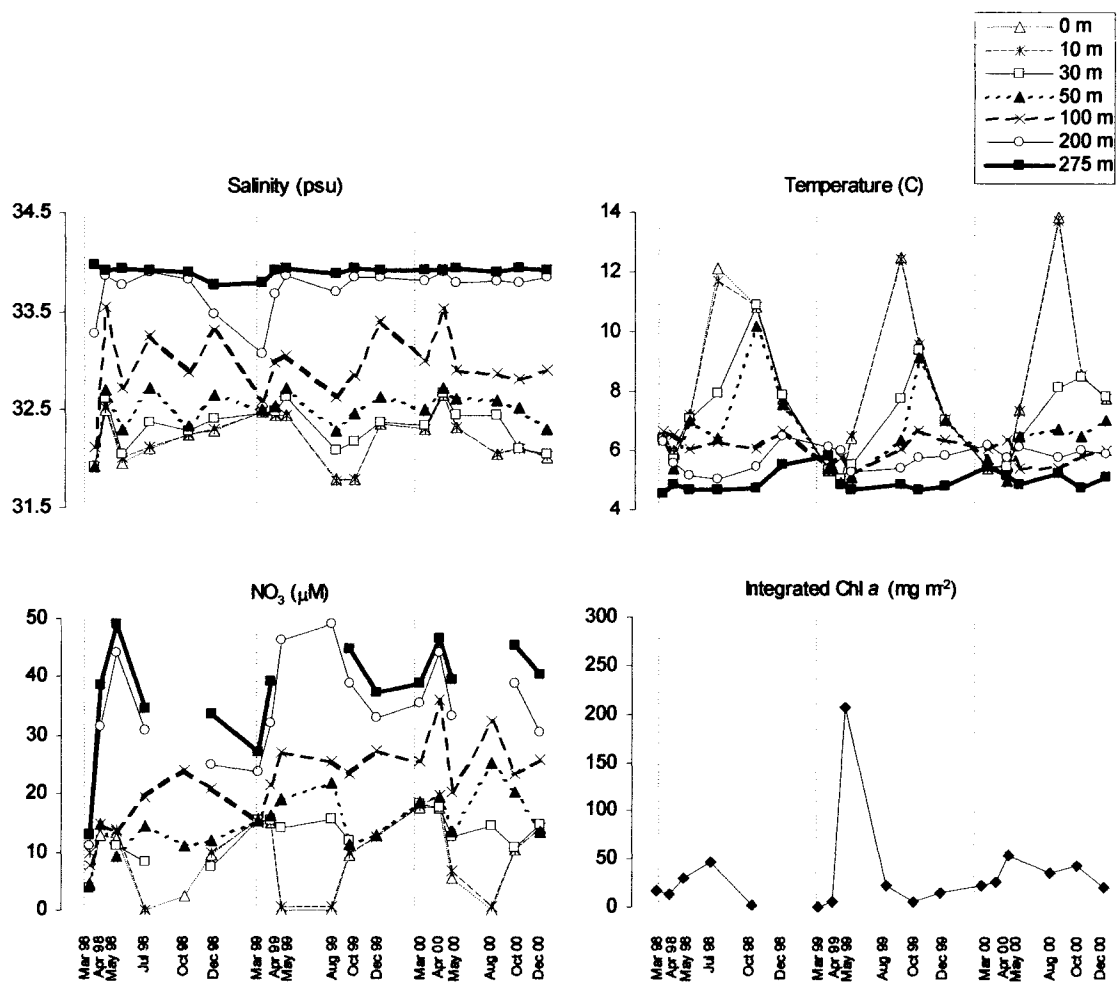


Figure 2.13 Time series at GAK 9 of salinity, temperature, nitrate and integrated chlorophyll *a* concentrations (0-50 m) March 1998 – December 2000. Dashed lines indicate March data.

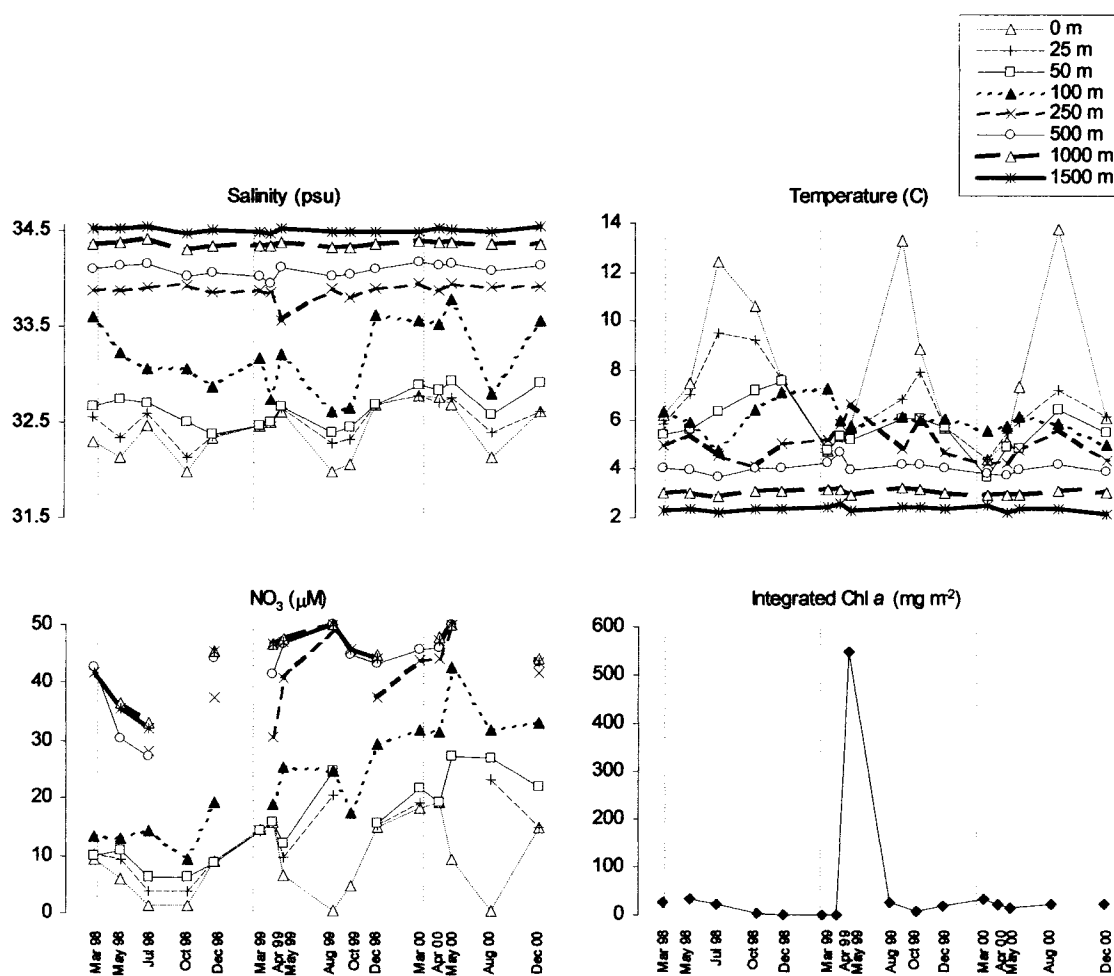


Figure 2.14 Time series at GAK 13 of salinity, temperature, nitrate and integrated chlorophyll *a* concentrations (0-50 m) March 1998 – December 2000. Dashed lines indicate March data.

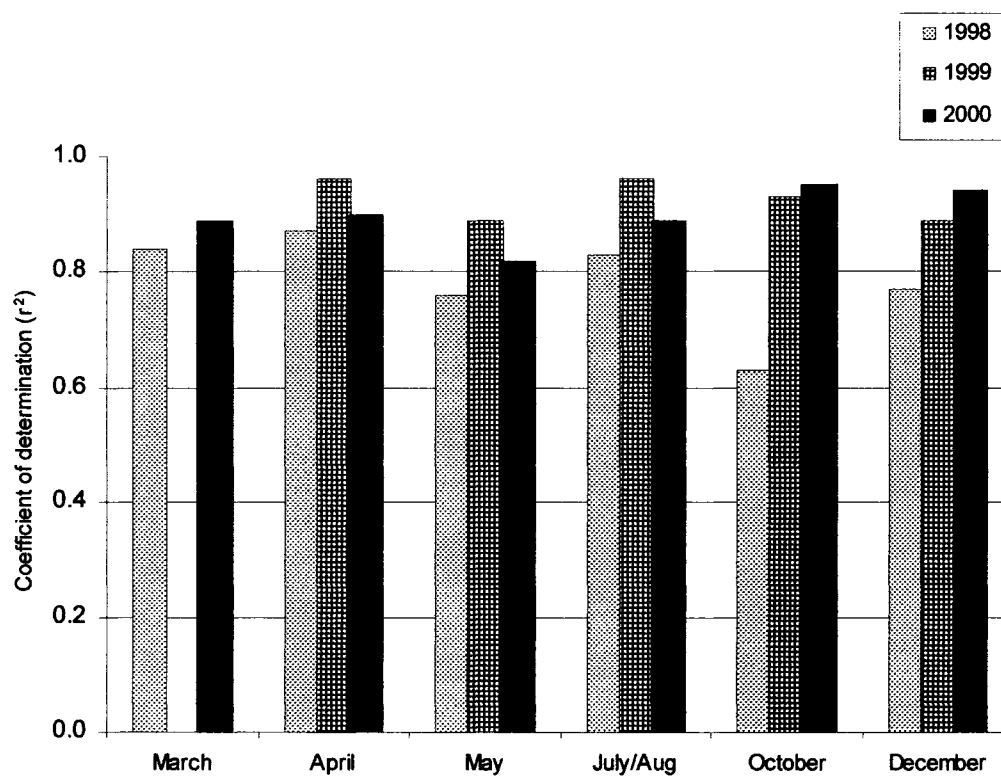


Figure 2.15 Coefficient of determination, r^2 , between salinity and nitrate at all stations for depths greater than 75 m along the Seward Line for March 1998 – December 2000.

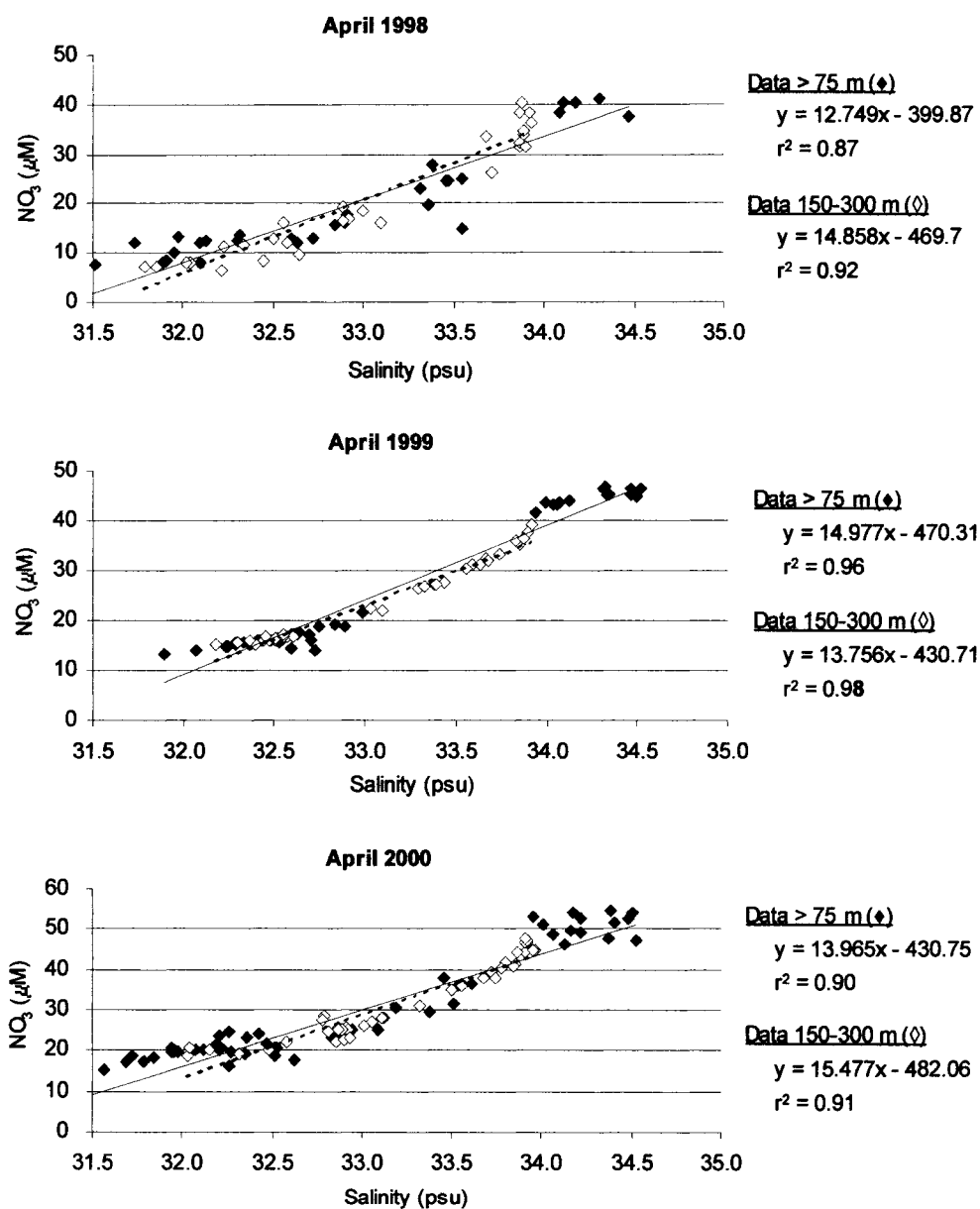


Figure 2.16 Salinity and nitrate relationships at depths > 75 m for April 1998 – 2000 (open diamonds = 150-300 m depths). Solid regression line represents all data > 75 m while dashed regression line represents 150-300 m.

Chapter 3. Spatial variability in the distribution of nutrients and chlorophyll *a* over the northern Gulf of Alaska shelf and slope and within Prince William Sound

3.1 Abstract

The northern Gulf of Alaska (GOA) has proven to be a very spatially dynamic and variable region. Physical, chemical, and biological data from Seward Line occupations in 1998, 1999, and 2000 was analyzed initially (Chapter 2) and established that the euphotic zone undergoes an annual cycle of nutrient drawdown and replenishment complicated by cross-shelf and interannual variability. Bottom waters experienced a seasonal onshore flux of deep, nutrient-rich slope waters that extended across the shelf creating a nutrient reservoir over the deep inner/middle shelf that differed in strength annually.

Physical, chemical, and biological data from additional cross-shelf transects and transects within Prince William Sound (PWS) collected in 1998, 1999, 2000, and 2001 were examined in this chapter to determine the extent of spatial variability in the northern GOA in comparison to the previously analyzed Seward Line. The general annual cycle of nutrient drawdown and replenishment in the upper water column with spring/summer nutrient enrichment at depth was similar over the shelf/slope and in PWS; however, spatial variability was found in the timing and extent of these dynamics. The shelf/slope data showed that the timing and degree of nutrient depletion depends primarily on proximity to the coast while the strength and extent of the onshore flux depends primarily on the bathymetry. Thus, it became clear that the Seward Line and the various other cross-shelf transects are unique due to their location, cross-shelf extent, and bathymetry. For instance, fresh surface waters were occasionally detected offshore over the middle shelf downstream of PWS, which is believed to be due to the retroflexion of the Alaska Coastal Current (ACC) as it passes the Chiswell Islands. Over the Seward Line shelf break and slope, evidence of recurring frontal dynamics was found due to the position of

the shelf break front, the onshore extent of the Alaskan Stream, and/or the passing of mesoscale slope eddies. The strongest impact of a passing slope eddy was detected in the spring of 1999 and less so in the late spring/early summer of 2001. Hinchinbrook Canyon was found to consistently have high salinity, nutrient-enriched bottom waters suggesting this bathymetric feature plays an important role in the harboring and transport of deep, nutrient-rich slope waters onto the shelf and into PWS. Cross-shelf transects upstream of PWS revealed that the deeper shelf regions serve as nutrient reservoirs while the region downstream of Kayak Island demonstrated the effect of the Kayak Eddy. The winter-spring near surface coastal waters upstream of PWS were generally warmer, saltier, and higher in nutrients than those downstream showing that PWS does have an influence on the upper coastal waters.

In 2001, nutrient drawdown and the spring bloom appeared earlier (April) in PWS than over the shelf/slope, then phytoplankton biomass in PWS reached its annual maximum in May when nutrient depletion was evident within the upper 20 m. The phytoplankton bloom over the shelf/slope occurred later in the spring (May) with lower overall biomass than in PWS. By July and August 2001, the surface waters in PWS and over the shelf/slope were nutrient depleted; however, nutrients were replete within and just below the euphotic zone. The mean N:Si and N:P ratios in PWS and over the shelf/slope generally indicated rapid drawdown of silicate and phosphate in the spring followed by more rapid nitrate drawdown in the summer. A closer look at the spatial dynamics in PWS revealed that the western portion of Montague Strait was generally fresher and cooler than the eastern portion, with higher phytoplankton biomass and earlier nutrient drawdown.

3.2 Introduction

The Seward Line was discussed and examined in great detail in Chapter 2. This transect was given highest sampling priority during each cruise since it encompassed both shelf and slope waters. Nutrient data from the Seward Line provided a recent example of nutrient dynamics across the northern GOA shelf and slope. An annual nutrient cycle

was described and interannual variability was observed. The results showed that the euphotic zone undergoes an annual cycle of nutrient drawdown in the spring and summer followed by replenishment in the fall in response to physical dynamics and phytoplankton activity. Upper water column nutrient concentrations are reduced to limiting or near limiting conditions by seasonally high phytoplankton chlorophyll biomass with a large degree of spatial variability in the timing, duration, and extent of nutrient drawdown. The summer onshore flux of deep, nutrient-rich slope water onto the inner and middle shelves creates a nutrient reservoir that is later mixed throughout the water column by winds and thermohaline processes in fall and winter. Interannual variability in the physical environment, nutrient concentrations, and phytoplankton biomass were also observed along the Seward Line.

It remained unclear however, how well the Seward Line represented the northern GOA shelf/slope region or how the shelf/slope region was different or similar to PWS. We hoped to answer the following questions:

1) Does the whole northern GOA shelf region experience nutrient limitation in the spring and summer? 2) Does the whole northern GOA shelf region experience a summer onshore flux of deep, high salinity, nutrient-rich slope water? 3) And if so, is it uniform or variable spatially? 4) Do nutrient reservoirs form over other regions of the northern GOA shelf in addition to the inner shelf portion of the Seward Line? 5) How do the physical structure and the nutrient-phytoplankton dynamics in PWS compare to those over the northern GOA shelf/slope? 6) Are there any prevailing spatial nutrient dynamics over the GOA shelf/slope or in PWS? 7) How do mesoscale slope eddies affect nutrient-phytoplankton dynamics over the outer GOA shelf and slope? In an attempt to answer these questions the physical, chemical, and biological data collected from various cross-shelf transects and transects within PWS in 1998, 1999, 2000, and 2001 were examined and compared in an attempt to describe the spatial nutrient dynamics over the northern GOA shelf.

3.3 Methods

3.3.1 Extended study area: The northern Gulf of Alaska and Prince William Sound

The data collection methods were described in detail in the methods sections 1.3.1 and 1.3.2. These included the collection methods and the chemical measurements of the nitrate/nitrite, silicate, phosphate, ammonium, and chlorophyll *a* concentrations.

The data discussed in this chapter include physical, chemical, and biological data collected from various cross-shelf transects and transects within PWS throughout 1998, 1999, 2000, and 2001. The cross-shelf transects include: the Cape Fairfield Line (CF), the Cape Cleare Line (CC), the Cape Cleare Southwest Line (CCSW), the Cape Cleare Southeast Line (CCSE), the Along Hinchinbrook Canyon Line (AHC), the Hinchinbrook Entrance Line (HE), the Prince William Sound West Line (PWSW), and the Ragged Island Line (RI) (Fig. 3.1). Data was also collected within Prince William Sound (PWS) along the Hogan Bay Line (HB), the Montague Strait Line (MS), and at stations in Knight Island Passage (KIP, PWS) (Fig. 3.1). The cruises during which these transects were occupied are shown in Table 3.1.

Cross-shelf transects near the Seward Line provided inner and middle shelf data from upstream and downstream of the Seward Line. The Cape Fairfield Line (CF) and Ragged Island Line (RI) are upstream and downstream, respectively, of the Seward Line (GAK). These transects extend seaward perpendicular to the shoreline across the shelf towards GAK 4 (Fig. 3.1). The CF Line was given high sampling priority since it provided a dense sampling regime of inner and middle shelf waters within the ACC in a region where the ACC is an east/west feature with little topographic steering (Danielson, S., personal communication). Therefore, this transect was sampled during every cruise. The CF Line consists of 15 stations that extend ~50 km offshore from CF 1. Only the odd numbered stations were sampled for nutrient concentrations and chlorophyll *a* concentrations, due to the closeness of the stations which led to time constraints. Along CF, depth increases from ~85 m near-shore at CF 1 to 160-193 m offshore (Fig. 3.2). The RI transect was sampled intermittently throughout the years as time and weather

permitted. The RI Line consists of 10 stations that extend ~80 km offshore. The RI Line crosses the Seward Line at GAK 4 (RI 9) with the last station, RI 10, just south of CF 15.

Transects upstream of the Seward Line near the entrances to Prince William Sound were also sampled intermittently throughout the years. These included the Hinchinbrook Entrance Line (HE) and the Along Hinchinbrook Canyon Line (AHC), which are near Hinchinbrook Entrance, as well as the Cape Cleare Line (CC), the Cape Cleare Southwest Line (CCSW), the Cape Cleare Southeast Line (CCSE), and the Prince William Sound West Line (PWSW), which are near the Montague Strait entrance (Figs. 3.1 and 3.2). Even farther upstream, samples were collected from the Cape Suckling Line (CS) in December 1999, which consists of 9 stations (CS 0-8) that extend ~66 km across a relatively narrow shelf and over the inner slope. Then in May 2000 samples were collected from the Copper River Line (CR), which consists of 6 stations that span ~56 km across a broad shelf region downstream of Kayak Island.

Samples were also collected from within PWS in Montague Strait and Knight Island Passage (Figs. 3.1 and 3.2). The Hogan Bay Line (HB) and Montague Strait Line (MS) span Montague Strait, with HB to the north of MS. Stations were also occasionally occupied in the western Sound in Knight Island Passage (KIP 1-3 and PWS 1-2), which are located in a deeper region of the Sound with depths ranging to ~742 m at PWS 2.

3.4 Results

3.4.1 Spatial Variability over the northern GOA shelf/slope

3.4.1.1 Averaged annual cycle at Cape Fairfield station 7 (CF 7)

A four-year averaged (1998-2001) annual cycle of the physical and chemical distributions at discrete depths from Cape Fairfield station 7 was calculated to compare to the inner and middle shelf Seward Line stations discussed in the previous chapter in section 2.4.1.2 with an upstream station (see Figs. 2.7 and 2.8). More specifically, CF 7 was chosen because it is approximately equidistance from the coastline and the Seward

Line. CF 7 lies ~21 km offshore of coastal station CF 1 within the ACC at ~182 m depth (Fig.3.1).

In late winter (March), the water column at CF 7 was well mixed with salinities, temperatures, and nutrient concentrations similar to those measured in the upper 100 m at GAK 1 (Fig. 3.3). In the spring (April and May), the water column began to warm and stratify as the bottom waters, below 50 m, became more saline. Also at this time, the upper 10 m nutrient concentrations had decreased since March. By July and August (summer), the water column was strongly stratified. The upper 20 m reached annual minimum concentrations of nitrate, silicate and phosphate with depleted concentrations in the upper 10 m (as defined in section 2.4.1.2). Meanwhile, the bottom nutrient concentrations reached annual maximum concentrations of $30.4 \mu\text{M NO}_3^-$, $41.8 \mu\text{M Si(OH)}_4$ and $2.4 \mu\text{M PO}_4^{3-}$. In October (fall), the water column was less stratified as the upper 100 m was mixed due to the onset of winter wind mixing. Consequently, nutrient concentrations in the upper 20 m increased while nutrient concentrations at 30-100 m decreased due to mixing of the upper water column. By December, the upper 100 m nutrient concentrations were more homogeneous yet were lower than those measured in late winter. Averaged ammonium concentrations were low ($<1.2 \mu\text{M}$) throughout the averaged annual cycle.

Chl *a* concentrations measured at CF 7 were low ($< 1.0 \mu\text{g l}^{-1}$) in the early spring (March and April) and fall (October and December) then annually high in late spring and summer (May, July, and August) with the highest chl *a* concentration measured in May 2000 ($7.6 \mu\text{g l}^{-1}$) (Fig. 3.4).

3.4.1.2 Annual cycle at Along Hinchinbrook Canyon station 5 (AHC 5)

Transects upstream of the Seward Line near the entrances to Prince William Sound were sampled intermittently throughout 1998, 1999, 2000, and 2001. A central station on the Along Hinchinbrook Canyon line, AHC 5, was selected to monitor the possible fluxes up the canyon and across the shelf to the entrance of PWS. Data were collected from AHC 5 during ten cruises: April 2001, May 2000 & 2001, July 1998 & 2001, August 1999, 2000, & 2001, and December 1998 & 1999 (Table 3.1). The annual

cycle is presented as a scatter plot of the data grouped by month (Fig. 3.5). AHC 5 lies ~45 km south of coastal station AHC 1 within the ACC at ~208 m depth (Fig.3.1).

In early spring, April (2001), the water column at AHC 5 was well mixed with slightly higher water column averaged salinities and temperatures than measured at GAK1, GAK 4, and CF 7 (Figs. 3.5 and 3.6). April (2001) water column averaged nutrient concentrations at AHC 5 were similar to those at the other shelf stations ($18.1 \mu\text{M NO}_3^-$, $24.1 \mu\text{M Si(OH)}_4$ and $1.8 \mu\text{M PO}_4^{3-}$). In late spring (May), the water column at AHC 5 began to stratify as upper water column nutrient concentrations decreased while the bottom nutrient concentrations increased. By July and August, the water column was strongly stratified with annual minimum nutrient concentrations in the upper water column and annual maximum concentrations in the bottom waters. Depleted nitrate concentrations were measured in the upper ~15 m in July. By August, depleted nitrate, silicate, and phosphate concentrations were measured in the upper 10-25 m. Summer bottom salinities among AHC 5, CF 7, GAK 1, and GAK 4 were consistently highest at AHC 5; however, summer bottom nutrient concentrations were highest at GAK 1 in 1998 and 1999 but highest at AHC 5 in 2000 and 2001. By December, the upper water column nutrient concentrations had been replenished since summer and fall, while the bottom water column nutrient concentrations had decreased since the maximum concentrations in summer. Ammonium concentrations were low ($< 2.4 \mu\text{M}$) throughout the years and seasons sampled.

3.4.1.3 An extended view of the spatial dynamics, spatially and temporally

The following cross-shelf transects were occupied regularly and/or opportunistically throughout 1998, 1999, 2000, and 2001 depending on time and weather in this general order of priority: Seward (GAK), Cape Fairfield (CF), Along Hinchinbrook Canyon (AHC), Hinchinbrook Entrance (HE), Cape Cleare Southeast (CCSE), Cape Cleare (CC), Cape Cleare Southwest (CCSW), Prince William Sound West (PWSW), Ragged Island (RI), Cape Suckling (CS), and Copper River (CR) (Fig. 3.1, Table 3.1). Physical, chemical, and biological data from these various transects

discussed in this section provide further insight into the spatial nutrient dynamics over the northern GOA shelf/slope.

Along and near the Seward Line, recurring cross-shelf variability was detected throughout 1998, 1999, 2000, and 2001. For example, distinctly fresh surface waters were regularly detected over the middle shelf. This surface feature was detected throughout the years and seasons and was positioned anywhere between GAK 3 and 5i. At times this feature was narrow (< 20 km), detected at 1 or 2 stations; while at other times it was broad (~30-50 km), extending across 4 or 5 stations. At times, nutrient and chl *a* distributions were clearly affected by this feature. For example in October 2000, the upper ~20 m at GAK 3-5 were distinctly fresh and warm with reduced nutrient concentrations and elevated chl *a* concentrations (Fig.3.7). This middle shelf feature was most physically evident in March and April 2001 by markedly fresh, cool surface waters (Fig. 3.6). These fresh, cool surface waters were also detected at the off-shore Cape Fairfield stations (as far inshore as CF 9) in the spring of 2000 (March, April, May) and 2001 (April, May) (Figs. 3.6, 3.8, and 3.9). Further offshore over the shelf-break and slope, distinct changes in the upper water column salinities were intermittently detected. In April 1998, December 1999, and April 2000 surface salinities increased by up to 0.8 psu between GAK 6 and 7 (Fig.3.10). Moreover, in December 1999, silicate concentrations (chl *a* concentrations) were markedly reduced (elevated) at the off-shore stations GAK 7-13 compared to the shelf stations. In March 1998, August 1999, October 1999, March 2000, May 2000, December 2000, April 2001, and December 2001 salinities in the upper ~50 m were noticeably higher at GAK 11-13 compared to GAK 10 and inshore (Figs.3.6, 3.8, and 3.11). At other times (July 1998, December 1998, March 2001, August 2001, October 2001, and December 2001), the upper water column salinities increased between adjacent stations between GAK 7i and 10. In the winter, spring, and fall months the higher salinity off-shore surface waters were also generally cooler than the shelf waters.

Downstream of the Seward Line, data were collected from the RI transect throughout 1999, 2000, and 2001 (Table 3.1). When sampled, salinities and nutrient

concentrations throughout the water column in the near-shore portion of RI were consistently lower than those measured in the near-shore portions of the GAK and CF lines (see Figs. 3.8, 3.10, 3.11, 3.12, and 3.13). Furthermore, the fresh coastal waters generally extended farther offshore (closer to GAK 4/RI 9) along RI than along GAK, but not as deep. For example, in August 1999, salinities at RI 1-6 were < 31.0 psu in the upper 40 m with salinities between 32.7 and 32.8 psu below 150 m (Fig. 3.11). By comparison at stations GAK 1-4, salinities < 30.8 psu were measured at GAK 1-2 in the upper 40 m while salinities were between 32.6 and 33.2 psu below 150 m. Furthermore, nutrient concentrations (temperatures) throughout the water column at stations RI 1-5 were lower (warmer) than those measured at GAK 1-4 and CF 1-15 in August 1999. Offshore, the salinities, temperatures, and nutrient concentrations at RI 7-10 were more similar to those measured at the nearby GAK and CF stations with higher (lower) water column salinities and nutrient concentrations (temperatures) than the near-shore stations.

Over the shelf offshore of Hinchinbrook Entrance, the AHC and HE transects were sampled intermittently throughout 1998, 1999, 2000, and 2001 (Table 3.1). During the AHC occupations, the bottom salinities and nutrient concentrations were commonly enriched compared to the other shelf stations sampled at that time (see Figs. 3.6, 3.8, 3.9, 3.10, 3.11, and 3.13). Generally, the bottom salinities and nutrient concentrations were greater than ~32.8 psu, ~22 $\mu\text{M NO}_3^-$, ~32 $\mu\text{M Si(OH)}_4$ and ~2.0 $\mu\text{M PO}_4^{3-}$. Along the HE transect, the bottom salinities and nutrient concentrations at the deeper stations at the head of the canyon (HE 10 and 11) were consistently higher than those measured at the other HE stations (see Figs. 3.6, 3.8, 3.9, 3.10, 3.13).

Offshore and downstream of Montague Island and Montague Strait, samples were collected from CC, CCSW, and PWSW in July 1998, August 1999, and October 1999. Along CC and CCSW, at stations < 70 m deep (CC 1-3 and CCSW 1-2) the water column salinities were low while the lower water column nutrient concentrations were low compared to the other shelf stations (less than: 32.1 psu, 23.8 $\mu\text{M NO}_3^-$, 28.9 $\mu\text{M Si(OH)}_4$ and 1.5 $\mu\text{M PO}_4^{3-}$) (Fig. 3.11). Of these three transects, the near-shore upper 50 m mean salinities were lowest along PWSW during the times sampled. The bottom

salinities and nutrient concentrations along these three transects increased with depth and distance off-shore. In July 1998 and August 1999, the off-shore deep (> 150 m) salinities and nutrient concentrations along CC, CCSW, and PWSW were similar to or higher than those measured nearby at depths below 150 m along CF. However, in October 1999, salinities and nutrient concentrations below 150 m were enriched along CC compared to those measured below 150 m along CCSW, PWSW, and CF (data not shown).

Samples were collected from transects upstream of PWS along the Cape Suckling transect (CS) in December 1999 and along the Copper River transect (CR) in May 2000. Along CS, salinities and temperatures in the upper 50 m were low near-shore (CS 0-1, range = 30.2-31.9 psu, 5.7-7.4 °C) then increased off-shore to an average of 32.3 psu and 7.8 °C at CS 2-7 (Fig. 3.10). In the upper 50 m over the slope at CS 8, salinities were notably higher (mean = 32.6 psu) while temperatures were lower (mean = 6.6 °C) than those at the inner stations. Nutrient concentrations in the upper 50 m along CS, and the other shelf stations, were uniform. The upper 50 m mean nitrate and phosphate concentrations along CS were similar to those measured downstream across the shelf along AHC, except for higher concentrations near-shore. Upper 50 m mean silicate concentrations along CS were consistently lower than those measured along AHC with the lowest concentrations near-shore. Along CS, the bottom shelf waters were salinity and nutrient enriched compared to the other shelf transects, especially at the deeper (> 200 m) mid-shelf stations. Nitrate and silicate concentrations from CS 8 at 500, 1000, and 1300 m were lost due to analytical error; however, phosphate concentrations in the slope waters below 500 m were higher (by $\sim 0.4 \mu\text{M PO}_4^{-3}$) than those over the slope along GAK. In May 2000, the upper 50 m along CR were comparatively stratified with salinities between 30.8 and 32.1 psu (Fig. 3.8). At CR 3-5, the upper 50 m were well mixed with relatively warm temperatures, low salinities, and low nutrient concentrations subsurface (20-50 m) compared to the inshore and offshore CR stations where the upper 50 m was more strongly stratified with cooler temperatures, higher salinities, and higher nutrient concentrations subsurface (20-50 m). Nutrient concentrations in the upper 50 m at CR 3-5 were low compared to those at the other shelf stations while mean station chl *a*

concentrations at CR 1-4 were greater than the average for the shelf ($1.37 \mu\text{g l}^{-1}$). At depth, the highest bottom salinities, nitrate concentrations, and phosphate concentrations from CR were measured at the deepest CR stations, CR 2 and 3. Bottom silicate concentrations from CR 2-4 were lost due to analytical error.

In order to further examine the data for along-shelf variability, salinity, temperature, and nutrient profiles from various near-shore shelf stations and PWS stations were plotted together. The most extensive along-shelf sampling occurred in December 1999 and May 2000 when samples were collected upstream of PWS along CS and CR, respectively and downstream of Ragged Island (RI) along Gore Point (GP) transect and Pye Island (PI) transect, respectively (see Figs. 3.1, 3.8, and 3.10). In December 1999, the following ten stations were plotted together: HB 2, MS 2, CS 3, HE 3, HE 9, AHC 2, CF 3, GAK 1i, RI 3, and GP 2 (Fig.3.14). The salinity profiles show that in the upper 100-150 m salinities were higher offshore and upstream of Hinchinbrook Entrance, with the highest salinities at the upstream location, CS 3, while the lower salinities were in PWS and at GAK 1i. Similarly, temperatures in the upper 100-150 m were warmest at the upstream location, CS 3, with cooler temperatures in the upper 20-30 m downstream from PWS. The nutrient profiles showed generally higher nutrient concentrations in the upper 100-150 m offshore and upstream of Hinchinbrook Entrance with the lower concentrations in PWS and at GAK 1i. The surface waters at these coastal station had the following upstream to downstream ranges: 32.2-30.4 psu, 7.8-6.3 °C, 14.7-9.5 $\mu\text{M NO}_3^-$, 20.4-10.3 $\mu\text{M Si(OH)}_4$, and 1.3-0.8 $\mu\text{M PO}_4^{3-}$. Among the deeper stations, salinities (temperatures) and nutrient concentrations below 150 m were relatively high (low) in PWS at MS 2 and at the downstream location, GP 2.

In May 2000, the following eleven stations were plotted together: HB 2, MS 2, *CR 3*, HE 3, HE 9, AHC 2, *CC 3*, CF 3, GAK 1i, RI 3, and *PI 2* (stations different from Dec 99 are in italics) (Fig.3.15). In the upper 10-100 m, salinities were generally higher offshore of Hinchinbrook Entrance and lower in PWS and at GAK 1i. Salinities in the upper ~50 m at CR 3 were relatively low. The warmer upper water column temperatures were measured in, around, and upstream of PWS while the coolest temperatures were

measured subsurface (30-150 m) in PWS. The higher upper water column (upper 20-50 m) nutrient concentrations were measured at AHC 2, CC 3, and CF 3 while the lower concentrations were generally measured in PWS, at CR 3, and at GAK 1i. The surface waters at these coastal stations had the following overall ranges: 30.3-31.4 psu, 6.6-8.5 °C, 0.1-10.7 $\mu\text{M NO}_3^-$, 0.6-16.3 $\mu\text{M Si(OH)}_4$, and 0.3-0.9 $\mu\text{M PO}_4^{3-}$. The highest nitrate and phosphate concentrations below 50-75 m were measured in PWS, in addition to relatively high silicate concentrations at HB 2 below 100 m.

Data collected from HB 2, MS 2, HE 3, HE 9, AHC 2, CCSE 2, CF 3, GAK 1i, and RI 3 in July 2001 were also plotted to examine summer conditions along the inner shelf (Fig. 3.16, also see Fig 3.13). Surface salinities ranged from 23.7-31.3 psu with the lower salinities in PWS and offshore of Hinchinbrook Entrance while surface temperatures were more uniform (10.9-12.6 °C). Surface nutrient concentrations were $< 0.9 \mu\text{M NO}_3^-$, $< 3.5 \mu\text{M Si(OH)}_4$, and $< 0.8 \mu\text{M PO}_4^{3-}$, except for higher silicate concentrations (9.1 and 14.8 $\mu\text{M Si(OH)}_4$) offshore of Hinchinbrook Entrance. At depths below 75 m, nutrient concentrations were highest in PWS.

3.4.1.4 The effect of slope eddies on nutrient distributions

Mesoscale eddies in the GOA are generated in the Alaska Current along the British Columbia-Alaska coast (Okkonen et al., 2001; Melsom et al. 1999). Melsom et al. (1999) state that “interannual variability in the upper ocean coastal circulation in the eastern GOA is linked to ENSO phenomenon in the tropical Pacific Ocean via coastal Kelvin waves and atmospheric teleconnections.” They further explain that “El Niño events destabilize the Alaska Current which results in the formation of multiple strong anticyclonic eddies along the coast, which slowly propagate into the GOA where they can survive for more than 1 year.” Their model results and observations “demonstrated that the high-latitude ocean responds strongly to ENSO events, having memory over thousands of kilometers and many years.” Okkonen et al. (2001) likewise state that moderate-to-large amplitude eddies in the GOA “are generated in the in the Alaska Current during years in which the wind forcing in the eastern GOA promotes strong downwelling along the British Columbia-Alaska coast and such wind conditions often,

but not always, occur in association with ENSO events.” Throughout the years included in this study, slope eddies in the northern GOA were scarce in 1998, prevalent throughout 1999, then intermittent in 2000 and 2001 which suggests a one to two year time lag between the generation of eddies in the eastern GOA and their passing through the northern GOA, assuming more eddies were generated in 1997-1998, which encompassed a very strong El Niño (see Table 3.1).

SSHA data from altimeter ground track D89, prepared and analyzed by Steve Okonnen, revealed that long-lasting, slow moving slope eddies were evident over the northern GOA slope downstream from the Seward Line during the following general time frames: March-May 1999, August-October 1999, September-November 2000, and June-July 2001 (Okonnen, 2003 and personal communication) (Fig. 3.17). Smaller, faster eddies were evident in December 1998, July 1999, December 1999, April 2000. Slow moving ($\sim 1.5 \text{ km d}^{-1}$) eddies intersect ground track D89 ~ 2 -5 weeks after they intersect the Seward Line, while fast moving ($\sim 4 \text{ km d}^{-1}$) eddies intersect ground track D89 ~ 5 -12 days after crossing the Seward Line (Okkonen, 2003). Although there is a time lag between the Seward Line and ground track D89 data the slope eddies may have been evident during the following GLOBEC cruises: December 1998, March 1999, April 1999, May 1999, August 1999, October 1999, December 1999, April 2000, August 2000, October 2000, May 2001, and July 2001 (see Table 3.1).

Evidence of these eddies in the physical, chemical, and biological data from the Seward Line was most apparent in the spring of 1999, particularly in May, when a slow moving eddy was evident in the SSHA data from March through May 1999 (Okonnen et al., 2003). In March 1999 (data not shown), the isohalines and nutriclines domed upward at GAK 11 and 12. The upper 50 m mean nitrate and silicate concentrations were slightly lower at GAK 9-13 than GAK 5i-8i (by $1.4 \mu\text{M NO}_3^-$ and $5.2 \mu\text{M Si(OH)}_4$). In April 1999 (data not shown), salinities and nutrient concentrations below 150 m were notably higher offshore of GAK 5i than inshore at GAK 1-5. Furthermore, over the slope at GAK 9i-13, the upper 50 m mean phosphate concentrations were low. Finally, in May 1999, the isohalines and nutriclines over the slope were doming toward the surface centered around

GAK 11 (Fig. 3.12). Nevertheless, nitrate and silicate concentrations in the upper water column were significantly lower at GAK 8-13 compared to the inshore shelf stations. For instance, nitrate and silicate concentrations in the upper 20 m over the shelf-break and slope were lower (range at GAK 8-13 = $0.9\text{--}8.6\ \mu\text{M NO}_3^-$ and $0.0\text{--}10.7\ \mu\text{M Si(OH)}_4$) than those over the inner and middle shelf (range at GAK 1-6 = $5.5\text{--}17.4\ \mu\text{M NO}_3^-$ and $12.6\text{--}24.9\ \mu\text{M Si(OH)}_4$). N:Si and N:P ratios in the upper 50 m averaged from GAK 8-13 were 1.1 and 12.5, respectively, compared to 0.7 and 20.5, respectively, averaged from GAK 1-6. Nutrient concentrations at depth (100-300 m) were enriched over the shelf-break and slope (range at GAK 8-15 = $22.7\text{--}50.0\ \mu\text{M NO}_3^-$, $27.6\text{--}75.1\ \mu\text{M Si(OH)}_4$, and $1.1\text{--}3.0\ \mu\text{M PO}_4^{3-}$) compared to the inner and middle shelf (range at GAK 1-6 = $13.0\text{--}24.2\ \mu\text{M NO}_3^-$, $19.0\text{--}29.3\ \mu\text{M Si(OH)}_4$, and $0.7\text{--}1.3\ \mu\text{M PO}_4^{3-}$). Additionally, the eddy likely enhanced primary productivity as chlorophyll *a* concentrations were much higher offshore, with concentrations at GAK 6-15 (GAK 1-5i) as high as $18.7\ \mu\text{g l}^{-1}$ ($1.86\ \mu\text{g l}^{-1}$) (see Fig. 2.3). A SeaWiFS image taken on May 15th, 1999 (~one week after the outer portion of the GAK Line was sampled) shows very high chl *a* concentrations over the northern GOA slope, encompassing GAK 9-13 (Fig. 3.18). No additional outer shelf/slope stations were occupied during this cruise to examine the spatial extent of this slope eddy.

The presence of a long-lasting, slow moving eddy passing over ground track D89 in June-July 2001 appears to have affected nutrient distributions measured along the Seward Line in May and July 2001. In May 2001, the upper water column offshore of GAK 5i was distinctly different from the near-shore waters with higher salinities and lower nitrate and silicate concentrations (Fig. 3.9). The upper 200 m had increased in salinity while nutrient concentrations below 125 m had increased since April 2001. By July, the upper water column nutrient concentrations over the shelf-break centered around GAK 8 were relatively high compared to those at the surrounding stations (Fig. 3.13). Salinity profiles showed doming isohalines at GAK 8-9i. Further offshore, nitrate was depleted from the upper ~10 m at GAK 9i-13, silicate was depleted from the upper ~10 m at GAK 11-13, and phosphate was depleted from the surface waters at GAK 11 and from

the upper ~20 m at GAK 12. Upper 50 m mean chl *a* concentrations were relatively low ($< 0.45 \mu\text{g l}^{-1}$) at GAK 7-9i then increased to $0.84\text{--}1.29 \mu\text{g l}^{-1}$ at GAK 10-13. Elsewhere, the upper 50 m salinities and temperatures at the offshore AHC (5-9) shelf stations and CCSE (3-8) shelf/slope stations were relatively fresh and warm compared to the offshore GAK (6-13) shelf/slope stations. The upper 50 m nitrate, silicate, and chlorophyll *a* concentrations at AHC 6-9 and CCSE 5-8 were more similar to those at the middle shelf GAK stations (GAK 3-6) than the shelf-break or slope GAK stations. The upper 50 m phosphate concentrations at AHC 6-9 and CCSE 5-8 were more similar to those at the GAK shelf-break stations (GAK 7-9).

During the other eddy events, no obvious effects were found in the upper water column nutrient or chlorophyll *a* distributions. During a few cruises slight increases or decreases in upper water column nutrient concentrations were measured over the shelf-break and slope. For example, in August 2000, upper 50 m mean nutrient concentrations (temperatures) were lower (warmer) at GAK 9-12 than the surrounding stations (GAK 7-8i and 13) by $\sim 4 \mu\text{M NO}_3^-$, $\sim 3 \mu\text{M Si(OH)}_4$, and $\sim 0.2 \mu\text{M PO}_4^{3-}$ ($\sim 1.4^\circ\text{C}$). Also in August 2000, the offshore ammonium concentrations in the upper 50 m were higher (up to $2.0 \mu\text{M}$) over the shelf-break (GAK 8-9i) and over the slope (GAK 13). In the deeper waters, a common feature in the physical profile over the shelf-break and slope was doming isohalines, generally centered around GAK 11 (March 1999, April 1999, May 1999, October 1999, October 2000, May 2001, and July 2001). Correspondingly, the subsurface (100-200 m) nutrient concentrations were commonly enriched over the shelf-break and slope compared to the same depths over the shelf.

3.4.1.5 Prince William Sound

The 2001 Annual Cycle

In 2001, physical, chemical and biological data were collected from the Montague Strait Line (MS) and the Hogan Bay Line (HB) during all seven cruises (March, April, May, July, August, October, December) (Fig. 3.1 and Table 3.1). From this year of data, the averaged annual cycle of the upper 50 m from PWS is described and compared to

analogous shelf/slope data. The shelf/slope data is comprised of upper 50 m data from the following transects: Seward (GAK), Cape Fairfield (CF), Cape Clear Southeast (CCSE), Hinchinbrook Entrance (HE), and Along Hinchinbrook Canyon (AHC). Spatial dynamics within PWS are then examined and described by taking a more detailed look at individual data from various cruises throughout the years.

In early spring (March), the water column in PWS was well mixed with annually high salinities and nutrient concentrations and annually low temperatures and chl *a* concentrations in the upper 50 m (mean = 31.5 psu, 5.5 °C, 16.9 $\mu\text{M NO}_3^-$, 25.6 $\mu\text{M Si(OH)}_4$, 1.3 $\mu\text{M PO}_4^{3-}$, and 0.48 $\mu\text{g l}^{-1}$ chl *a*) (Fig. 3.19). The corresponding mean N:Si and N:P ratios were 0.66 and 12.8, respectively. These upper water column conditions were similar to those over the shelf/slope except the average salinity was markedly higher (by 0.6 psu) over the shelf/slope (Fig. 3.20).

By April, nutrient concentrations in the upper 30 m in PWS had generally decreased since March, as the minimum concentrations decreased from 15.2 to 0.3 $\mu\text{M NO}_3^-$, 22.3 to 1.5 $\mu\text{M Si(OH)}_4$, and 1.0 to 0.6 $\mu\text{M PO}_4^{3-}$, with the lower concentrations measured at HB 1 and MS 1 (Fig. 3.6). The overall mean chl *a* concentration in PWS had increased since March to 2.93 $\mu\text{g l}^{-1}$, with the highest chl *a* concentration (7.70 $\mu\text{g l}^{-1}$) at HB 1. The chl *a* concentrations along HB were higher than those along MS, but both transects had the highest chl *a* concentrations at the western-most stations. Meanwhile, over the shelf/slope, surface nutrient concentrations did not decrease nor did chl *a* concentrations increase in April 2001, except for a few reduced nutrient concentrations at Cape Fairfield (CF) 1.

By May 2001, the upper 50 m mean nutrient concentrations in PWS decreased to 9.3 $\mu\text{M NO}_3^-$, 10.8 $\mu\text{M Si(OH)}_4$ and 1.0 $\mu\text{M PO}_4^{3-}$. Nutrient concentrations less than 2 $\mu\text{M NO}_3^-$, 5 $\mu\text{M Si(OH)}_4$ and 0.5 $\mu\text{M PO}_4^{3-}$ were present in the surface waters across both HB and MS (Fig. 3.9). Consequently, N:Si ratios and N:P ratios in the upper 10 m were < 0.5 and < 3.0, respectively. Since March, the mean N:P ratio decreased to 8.0 while the mean N:Si ratio increased to 0.82. May ammonium concentrations were much higher than those measured in April (< 1.9 μM), reaching the mean annual maximum (0.8 μM)

with the higher concentrations subsurface. Chl *a* concentrations also increased since April to the annual maximum (mean = $4.40 \mu\text{g l}^{-1}$), with the higher chl *a* concentrations ($> 8.91 \mu\text{g l}^{-1}$) subsurface along HB. Over the shelf/slope, nutrient concentrations in the upper 20-50 m generally decreased since April, especially near-shore along the HE, CF, and GAK lines (minimum = $5.0 \mu\text{M NO}_3^-$, $4.7 \mu\text{M Si(OH)}_4$ and $0.4 \mu\text{M PO}_4^{3-}$). The overall shelf/slope mean chl *a* concentration increased since April to $0.94 \mu\text{g l}^{-1}$, with the higher concentrations near-shore and subsurface, particularly along the GAK line.

In July 2001, the upper water column in PWS was strongly stratified as the upper 50 m mean temperature increased to 9.0°C and the mean salinity decreased to 31.1 psu. Nutrient concentrations in the upper 50 m were generally lower than those in May as the means decreased by $2.7 \mu\text{M NO}_3^-$, $0.2 \mu\text{M Si(OH)}_4$ and $0.02 \mu\text{M PO}_4^{3-}$. Nitrate, silicate, and phosphate concentrations $< 2 \mu\text{M}$, $5 \mu\text{M}$, and $0.5 \mu\text{M}$, respectively, were present within the upper 20 m while concentrations as high as $18.6 \mu\text{M NO}_3^-$, $22.5 \mu\text{M Si(OH)}_4$ and $1.9 \mu\text{M PO}_4^{3-}$ occurred at 50 m depth (Fig.3.13). The mean N:Si and N:P ratios reached annual minimums, 0.46 and 5.3 respectively, with the lower values (< 0.55 and 6.3, respectively) in the upper 20 m. Ammonium concentrations decreased slightly since May but remained seasonally high, with concentrations $> 0.7 \mu\text{M}$ subsurface (10-50 m). Overall, chl *a* concentrations were annually high but the overall mean chl *a* concentration decreased since May to $3.61 \mu\text{g l}^{-1}$. Over the shelf/slope, the upper water column was also much more stratified since May with low salinities, < 31 psu, within the upper 20 m near-shore and universally higher temperatures (mean = 9.2°C). Nutrient concentrations in the upper 20-30 m generally decreased since May with some concentrations less than $2.0 \mu\text{M NO}_3^-$, $5.0 \mu\text{M Si(OH)}_4$ and $0.5 \mu\text{M PO}_4^{3-}$. However, by 50 m, nutrient concentrations were as high as $15.0 \mu\text{M NO}_3^-$, $27.6 \mu\text{M Si(OH)}_4$ and $1.8 \mu\text{M PO}_4^{3-}$. The mean N:Si and N:P ratios decreased to 0.49 and 6.7, respectively with values < 0.38 and < 4.5 , respectively in the upper 20 m. Ammonium concentrations had increased since May reaching the mean annual maximum ($0.6 \mu\text{M}$), with concentrations $> 1.0 \mu\text{M}$ subsurface (20-50 m) and generally near-shore. The overall mean chl *a* concentration

also had reached the annual maximum ($1.32 \mu\text{g l}^{-1}$), with the higher chl *a* concentrations ($> 3.0 \mu\text{g l}^{-1}$) generally near-shore and subsurface (10-20 m).

In August 2001, the water column in PWS remained strongly stratified. The upper 50 m reached the mean annual maximum surface temperature (10.2°C) while the mean salinity was low (30.0 psu). The mean nitrate and silicate concentrations from the upper 50 m had increased slightly since July while the mean phosphate concentration continued to decrease. Nutrient concentrations $< 2 \mu\text{M NO}_3^-$, $5 \mu\text{M Si(OH)}_4$, and $0.5 \mu\text{M PO}_4^{3-}$ were present within the upper 10 m with concentrations as high as $17.4 \mu\text{M NO}_3^-$, $26.1 \mu\text{M Si(OH)}_4$ and $1.8 \mu\text{M PO}_4^{3-}$ by 50 m. The mean N:Si and N:P ratios had increased since July. Ammonium concentrations had decreased notably since July ($< 1.1 \mu\text{M}$), with the higher concentrations subsurface. The overall mean chl *a* concentration had continued to decrease since the peak in May with the higher chl *a* concentrations in the upper 20 m. The upper water column over the shelf/slope also remained strongly stratified reaching the mean annual maximum temperature (10.3°C) and the mean annual minimum salinity (31.2 psu). The 50 m mean nutrient concentrations continued to decrease to annual minimum values ($7.1 \mu\text{M NO}_3^-$, $11.6 \mu\text{M Si(OH)}_4$ and $0.9 \mu\text{M PO}_4^{3-}$). The mean N:Si and N:P ratios had decreased slightly since July to the annual minimums (0.48 and 6.0 respectively). Ammonium concentrations were annually high ($< 1.6 \mu\text{M}$) with the higher concentrations near-shore and subsurface. The overall mean chl *a* concentration decreased from the annual maximum in July to $0.68 \mu\text{g l}^{-1}$ as the chl *a* concentrations were now more evenly distributed across the shelf with the higher concentrations subsurface (10-20 m).

In PWS in October 2001, temperatures in the upper 10 m had decreased while temperatures below 20 m generally had increased since August. As a result, the upper 50 m means from August and October were very similar. The upper 50 mean salinity reached a minimum (29.6 psu). In the upper 20 m, silicate concentrations had increased since August to concentrations $> 6.7 \mu\text{M}$ while nitrate and phosphate concentrations had increased only slightly with concentrations $> 1.5 \mu\text{M}$ and $0.4 \mu\text{M}$, respectively. Below 30 m, nutrient concentrations generally had decreased since August. The mean N:Si and

N:P ratios had decreased from August. Ammonium concentrations were $< 0.7 \mu\text{M}$, with concentrations $> 0.2 \mu\text{M}$ in the subsurface waters (10-50 m) along MS. The overall mean chl *a* concentration had decreased since August with the higher chl *a* concentrations ($> 0.5 \mu\text{g l}^{-1}$) in the upper 10 m. Over the shelf/slope, surface temperatures had decreased while subsurface temperatures increased. The upper 50 m mean salinity had increased from the annual minimum in August to 31.6 psu, with salinities < 31.0 psu within the upper 40 m near-shore. Nutrient concentrations in the upper 20 m generally increased with the lower nutrient concentrations ($< 4 \mu\text{M NO}_3^-$, $10 \mu\text{M Si(OH)}_4$ and $1.0 \mu\text{M PO}_4^{3-}$) in the near-shore waters within the upper 30-50 m. The overall mean chl *a* concentration had decreased slightly since August with chl *a* concentrations $< 1.2 \mu\text{g l}^{-1}$ across the shelf/slope.

Finally, in December 2001, salinities in the upper 50 m in PWS had increased to > 30.5 psu while temperatures in the upper 100 m decreased to $< 7.8^\circ\text{C}$. Nutrient concentrations in the upper 20-40 m generally had increased since October to concentrations $> 8.7 \mu\text{M NO}_3^-$, $10.7 \mu\text{M Si(OH)}_4$ and $0.2 \mu\text{M PO}_4^{3-}$; consequently, the mean N:Si and N:P ratios had increased since summer and fall. Ammonium concentrations were annually low, $< 0.2 \mu\text{M}$. The overall mean chl *a* concentration reached the annual minimum ($0.18 \mu\text{g l}^{-1}$) with chl *a* concentrations $< 0.33 \mu\text{g l}^{-1}$. Over the shelf/slope, temperatures in the upper 75-100 m had decreased since October as the upper 50 m mean temperature dropped to 6.6°C while salinities were now > 31.5 psu except for some lower salinities near-shore. The upper 50 m means for nitrate and silicate increased since October while the mean for phosphate did not change. The overall mean chl *a* concentration reached the annual minimum ($0.20 \mu\text{g l}^{-1}$).

Spatial dynamics

Physical, chemical, and biological data collected from along Hogan Bay (HB) and Montague Strait (MS) transects and in Knight Island Passage (KIP 1-3 and PWS 1-2) throughout 1998, 1999, 2000, and 2001 established some general spatial trends in PWS (Table 3.1 and Fig. 3.1). (Knight Island Passage is a narrow, deep passage in the western portion of PWS). When sampled, the deeper, western HB and MS stations were

commonly more stratified than the eastern stations with fresher, cooler surface waters above nutrient-enriched, saline bottom waters, as demonstrated most clearly in April 2001 (Fig. 3.6, also see Figs. 3.8-3.13). Furthermore, in the early spring and fall, surface nutrient concentrations were generally lower while chl *a* concentrations were higher at the western stations compared to the eastern stations. In the western region of PWS, in Knight Island Passage, the upper 10-50 m were consistently fresher (and commonly cooler) than the HB and MS region while the deeper waters below 300 m in KIP were more saline and nutrient enriched, as demonstrated most visibly in April 2001 (Fig. 3.6, also see Figs. 3.8-3.13). In the winter, spring and fall, the upper 50 m mean nutrient concentrations at stations in Knight Island Passage were similar to or less than those at stations along HB and MS, while in the summer months, subsurface nutrient concentrations (10-50 m) were higher at the KIP stations than the HB and MS stations. Within PWS, salinity and nutrient concentrations below 50 m depth were similar to those over the shelf. Bottom salinities and nutrient concentrations were maximum in summer, e.g. July and August, in 2001.

3.5 Discussion

3.5.1 Spatial nutrient dynamics on the northern GOA shelf

Physical and chemical data from shelf stations CF 7 and AHC 5 compared to Seward Line shelf stations GAK 1 and GAK 4 showed that the general annual cycle over the northern GOA shelf is similar spatially. The euphotic zone begins the annual growing season with uniformly high nutrient concentrations followed by nutrient drawdown and surface depletion in the spring and summer, when phytoplankton biomass is highest, due to developing and strengthening stratification. In the fall and winter, phytoplankton biomass decreases while nutrients are replenished by wind mixing. Meanwhile at depth, dense, nutrient-rich waters move onto the shelf during late spring and summer when downwelling favorable winds diminish. There were, however, some noteworthy differences among these four shelf stations. The upper water column at GAK 1 had the largest annual cycle with comparably fresh, warm, and nutrient-depleted

surface waters in the summer and fall due to its coastal location. At depth, the strength of the summer onshore flux varied spatially with the most saline near bottom waters consistently measured in Hinchinbrook Canyon and the highest near bottom nutrient concentrations found over the deep inner shelf at GAK 1 or in Hinchinbrook Canyon.

Spatial dynamics over the northern GOA shelf were expanded by including data from additional cross-shelf transects sampled throughout 1998, 1999, 2000, and 2001. Offshore over the inner/middle shelf along the Seward Line a fresh surface water jet was intermittently detected throughout the years and seasons sampled. This freshwater feature is believed to be a retroflection of the ACC as it passes the Chiswell Islands and Chiswell Ridge (S. Danielson, personal communication). In the spring of 2000 and 2001, these fresher offshore waters were also detected farther upstream at the offshore Cape Fairfield stations demonstrating the expanse and seasonality of this feature. The coastal freshwater wedge downstream from the Seward Line across the Ragged Island (RI) Line generally extended farther offshore towards GAK 4, but was generally not as deep. This was also likely due to the deflection of the ACC offshore by the coastline and shoaling shelf in this coastal region downstream of the Seward Line. The deeper water column nutrients and salinities in the near-shore Ragged Island (RI) waters were not as enriched as the deeper upstream GAK waters. These observations suggest that this region of the northern GOA shelf is very dynamic due to the local bathymetry and coastline. However, additional measurements are necessary to determine the persistence or seasonality and the dynamics of the ACC flow in this portion of the shelf. Offshore over the outer shelf and slope, distinct changes in cross-shelf water mass characteristics indicated that shelf-break fronts, or the onshore edge of the Alaskan Stream, or edges of slope eddies were commonly found between GAK 6 and 11.

Upstream from the Seward Line near the main entrance to PWS, the bottom waters along Hinchinbrook Canyon (AHC) and at the head of the canyon (HE 10 and 11) were regularly enriched in nutrients throughout the years and seasons compared to the other shelf stations. This suggests that this bathymetric feature channels deep, nutrient-rich slope waters onto the inner shelf and probably into PWS.

The shelf region near the Montague Strait entrance to PWS was most comprehensively sampled in summer 1998 and 1999 and fall 1999 (Cape Cleare (CC), Cape Clear Southwest (CCSW), and Prince William Sound West (PWSW)). The shallower near-shore stations off Cape Cleare were relatively fresh with low bottom nutrient concentrations compared to the other shelf stations. The coastal waters along Prince William Sound West (PWSW), downstream of PWS in the ACC, were also fresh due to coastal inputs from the mainland and outflow from PWS. Bottom salinities and nutrient concentrations increased with depth and distance offshore along these transects as observed along the other cross-shelf transects. At the deeper offshore stations, which are situated in or near Bainbridge Trough, the lower water column nutrient concentrations were similar to or greater than those measured at depth along Cape Fairfield (CF). This demonstrates that this offshore region of the shelf had nutrient enriched bottom waters during the 1998 and 1999 seasonal onshore flux.

The shelf waters east of PWS were sampled in early winter 1999 and late spring 2000. In December 1999, the upper water column nitrate and phosphate concentrations near-shore were relatively high unlike the reduced concentrations at the near-shore stations downstream from PWS. Meanwhile, the upper water column salinities and temperatures were higher along Cape Suckling (CS) than those measured to the west. These differences were likely due to the outflow of fresh, cool, nutrient poor waters from PWS through the downstream transects. The distinctly cool, saline upper slope waters demonstrated the presence of a frontal feature over the slope off Cape Suckling. The deeper middle shelf waters along CS were saline and nutrient enriched compared to stations to the west, while the slope waters were enriched in phosphate compared to the western slope stations. In May 2000, the upper waters along Copper River (CR) were found to be thermally stratified and nutrient enriched near-shore and off-shore while they were well-mixed with warm, nutrient-poor waters in between. Phytoplankton biomass was higher near-shore, in the lee of Kayak Island. Royer et al. (1979) concluded that a permanent anticyclonic eddy exists to the west of Kayak Island that is established by the interaction of the ACC with the coastline and bathymetry. This eddy likely influenced

the physical, chemical, and biological distributions along this transect. The highest bottom salinities, nitrate concentrations, and phosphate concentrations were at the deeper near-shore stations. In summary, these two upstream transects exhibited cross-shelf variability and demonstrated that the deeper portions of the shelf in this region upstream of PWS act as nutrient reservoirs.

Profiles from various near-shore shelf and PWS stations sampled in December 1999 and May 2000 demonstrated the presence of along-shelf trends in salinity, temperature, and nutrient concentrations. During the winter and spring cases, the upper water column salinities, temperatures, and nutrient concentrations were generally higher upstream of PWS and offshore of Hinchinbrook Entrance than those within and downstream of PWS suggesting that PWS acts as a sink for inorganic nutrients during the winter and spring seasons. The ranges in the surface physical and chemical values in the winter and spring cases also demonstrated the degree of along-shelf variability in the coastal waters. The strong similarities between the Seward Line and PWS stations suggest the inner-shelf along the Seward Line is largely influenced by outflow from PWS. In May 2000 and July 2001, the lower water column nutrient concentrations were uniformly higher in PWS than over the inner shelf, demonstrating a reservoir affect in PWS that suggests that the lower water column is not thoroughly flushed each year. These higher bottom concentrations (but similar salinities) could also be due to recycling or remineralization of nutrients in PWS.

3.5.2 The effect of slope eddies on nutrient distributions

Okkonen et al. (2003) state that “anticyclonic eddies, propagating adjacent to the shelf, alter the structure of the shelf-break front and influence the shelf-slope exchange of water mass properties” and that “upwelling zones are established near the shelf-break in association with the leading and trailing flanks of anticyclonic eddies”. During many of the eddy-involved cruises, upwelling over the shelf-break and/or slope was evident in the salinity and nutrient distributions as a doming in the haloclines and nutriclines. In May 2001, the upper water column over the outer shelf and slope was distinctly different from the near-shore waters as the outer shelf and slope waters were well mixed, higher in

salinity, and collectively lower in nitrate and silicate. Then in July 2001, upwelling was evident at the shelf-break where the surface salinities and nutrient concentrations were locally high, while the slope waters were higher in phytoplankton biomass with depleted surface nutrient concentrations. However, the shelf-break and slope waters along AHC and CCSE did not show any evidence of eddy activity in July 2001. Okkonen et al. (2003) provided a schematic of the spring 1999 eddy showing the Seward Line near the leading flank in March then near the trailing flank in May. Upper water column nutrient concentrations were not greatly altered in March and April 1999 as nutrient concentrations were similar to or slightly lower offshore than inshore. But in May, upwelling associated with the trailing flank of the passing eddy enriched subsurface nutrients while a very strong phytoplankton bloom reduced surface nutrient concentrations. The nutrient ratios suggested rapid silicate and nitrate drawdown by the phytoplankton community within the trailing flank of the eddy. Slope eddies clearly affected the nutrient and phytoplankton distributions over the shelf-break and slope in May 1999, but in many cases the presence of a slope eddy was not clearly evident in the upper water column nutrient and phytoplankton distributions.

3.5.3 The annual cycle and spatial dynamics within PWS

Physical, chemical, and biological data collected in 2001 from the upper waters of Hogan Bay and Montague Strait in PWS provided an example of an annual cycle within PWS. This data from PWS was also directly compared to the 2001 northern GOA shelf/slope annual cycle to describe the primary differences between these two regions. In early spring, March and April 2001, the water column was well mixed after a windy winter season with slightly more surface stratification in PWS due to coastal freshwater inputs of melting snow and ice from the coastal mountains and glaciers. The pre-bloom nutrient ratios indicated the PWS and shelf/slope waters were silicate enriched and below the Redfield ratio of 16:1 before the onset of the spring phytoplankton blooms. By April, a phytoplankton bloom had developed in PWS and began drawing nutrients out of the euphotic zone. The change in the N:Si and N:P ratios in PWS from March to May indicated rapid silicate and nitrate drawdown suggesting the phytoplankton community

was dominated by siliceous species. Recent analyses of the phytoplankton community in PWS and along the Seward Line (April 1998 and May 1999) by Strom et al. (2001) found that large phytoplankton, mainly diatoms, dominated these waters under spring bloom conditions.

As the upper water column began to stratify in May, phytoplankton biomass in PWS was still much higher than that over the shelf/slope and reached the annual maximum with the highest biomass in the subsurface waters along HB. Nutrients were drawn out of the euphotic zone and were depleted from the upper 20 m. Low N:Si and N:P ratios in the surface waters of PWS indicated rapid nitrate drawdown at this time, but the increase in the overall N:Si mean since April indicated rapid silicate drawdown in the subsurface waters. Ammonium also reached the mean annual maximum in PWS in the subsurface waters. Over the shelf/slope, the upper water column was most strongly stratified near-shore due to increasing freshwater discharge. As a result, phytoplankton blooms developed near-shore while nutrients were drawn down, but were not limiting, and ammonium concentrations were high with the highest phytoplankton biomass and ammonium concentrations near-shore along the GAK line.

In July and August 2001, the upper water column in PWS and over the shelf/slope was strongly temperature and salt stratified. During this summer season, the surface waters in PWS were depleted of nitrate, silicate, and phosphate. Over the shelf/slope, surface nutrient depletion was evident, but not as uniformly. Also of note, the waters within and below the euphotic zone in PWS and over the shelf/slope were also nutrient-replete which shows nutrients were readily available just below the nutrient depleted surface layer. This suggests that the phytoplankton community was not entirely nutrient limited, so either primary production was limited by something else (such as micronutrient(s) or the lack of sunlight at depth) or grazing zooplankton maintained low biomass levels. Where stratification was the strongest, in PWS and near-shore due to coastal inputs, phytoplankton biomass and ammonium were high in the subsurface waters while nutrients were depleted or near depleted from the surface waters. The annually low (July and August) N:Si and N:P ratios and means in PWS and over the shelf/slope

confirm nitrate drawdown and depletion by the phytoplankton community during the summer months. In July, phytoplankton biomass in PWS was still much higher than over the shelf/slope, but had dropped slightly since the annual maximum in May. By August, phytoplankton biomass in PWS dropped to levels only slightly higher than those over the shelf/slope, where phytoplankton biomass was now more evenly distributed. The nutrient-replete subsurface layer suggests that the phytoplankton community in PWS was not nutrient limited but likely biomass was low due to other losses or pressures such as grazing.

In October 2001, the upper water column in PWS and over the shelf/slope began to cool and mix as upper water column temperatures became more homogenous and dropped below 11 °C. The mean salinity in PWS reached the annual minimum and was annually low over the shelf/slope due to seasonally high freshwater input. The surface layer in PWS was higher in phytoplankton biomass than that over the shelf/slope and it continued to be depleted of nitrate and phosphate, with concentrations that were not limiting available by 10 m (silicate concentrations were replete). These nutrient conditions indicate continued drawdown by a phytoplankton community not dominated by siliceous species or more replenishment of silicate from freshwater inputs in PWS. The mean N:Si and N:P ratios in PWS and over the shelf/slope were annually low suggesting extensive nitrate drawdown at this time of year. Phytoplankton biomass over the shelf/slope decreased only slightly since August and was fairly evenly distributed in October. The overall chl *a* mean from the shelf/slope data was higher than that from PWS suggesting that the environment over the shelf/slope was now more favorable for phytoplankton growth or phytoplankton biomass in PWS was lower due to losses such as grazing. Nutrient concentrations in the surface waters over the shelf/slope were no longer limiting as they were replenished due to weakening stratification. Surface nutrient concentrations within the ACC were lower indicating elevated assimilation by phytoplankton or less replenishment in these near-shore waters.

By December 2001, the upper water column over the shelf/slope and in PWS had become well mixed as salinities and nutrient concentrations generally increased while

temperatures decreased due to the onset of winter wind mixing. Phytoplankton biomass was annually low while nutrients were generally replete in the upper waters in PWS and over the shelf/slope.

Spatial differences were detected in PWS among the Montague Strait and Knight Island Passage regions. The surface waters in Montague Strait (HB and MS) were more stratified, fresher and cooler along the western edge of the strait due to the predominant westward winds and western boundary flow of the ACC. Consequently, in the spring and fall, phytoplankton biomass was higher and nutrients were drawn down more extensively at the western stations due to earlier and stronger stratification in the upper water column. To the northwest, the upper water column in Knight Island Passage was fresher and cooler than that in the Montague Strait region due to more coastal inputs to this inland region. Nutrient concentrations in the spring and fall were similar throughout the western and southern Sound, except for higher subsurface nutrient concentrations in the summer in Knight Island Passage, which is likely due to less extensive summertime mixing in this region due to its more sheltered location. From the handful of SeaWiFS images providing good coverage of the northern GOA and PWS available throughout 1998-2001, quite a few showed higher chlorophyll levels in Montague Strait and/or in the central Sound north of Hinchinbrook Entrance and around Knight Island (see Fig. 3.18). This suggests that these regions of PWS are more suitable for phytoplankton growth for reasons not yet identified.

3.6 Conclusions

The physical, chemical, and biological data from across and along the northern GOA shelf/slope and in PWS collected throughout 1998, 1999, 2000, and 2001 answered some fundamental questions about the spatial nutrient dynamics in this region. For starters, it was uncertain how well the Seward Line represented the northern GOA shelf/slope region. Principally, the additional cross-shelf transects confirmed that nutrient concentrations generally increase with depth and distance offshore. The comparison of annual cycles from GAK 1 and GAK 4 to CF 7 and AHC 5 revealed that

the upper water column over the northern GOA shelf undergoes a general annual cycle of drawdown, depletion, and replenishment while the bottom waters experience annual enrichment during the summer onshore flux. However, the shelf/slope data also showed that the timing and degree of nutrient depletion depends on proximity to the coast while the strength of the onshore flux depends primarily on the bathymetry. For instance, Hinchinbrook Canyon consistently harbored saline, nutrient-enriched bottom waters throughout the years and seasons indicating that this bathymetric feature acts as a nutrient reservoir and likely plays an important role in the transport of deep, nutrient-rich slope waters onto the shelf and possibly into PWS. Data from cross-shelf transects upstream of PWS revealed that the deeper shelf regions harbored nutrient enriched bottom waters; therefore, these troughs also serve as nutrient reservoirs like the deep inner shelf region of the Seward Line.

Along-shelf variability in the physical distributions and nutrient dynamics was also clearly evident. Coastal distributions downstream of the Seward Line were found to be different due to the changing coastline and shoaling bathymetry near the Chiswell Islands. The physical data indicate that the ACC shallows and widens and is deflected offshore downstream of the Seward Line where it is occasionally deflected back over the middle shelf. Further monitoring is needed to determine whether this is a seasonal or permanent feature and/or an eddy like feature and to understand how it affects the nutrient and phytoplankton dynamics. Along-shelf trends were found in the upper coastal waters in early winter and spring, where the upper water column salinities, temperatures, and nutrient concentrations were generally higher upstream of PWS. This demonstrates along-shelf variability and indicates that PWS does have an influence on the downstream coastal properties.

Spatial variations were also examined further offshore over the outer shelf and slope. The data showed recurring frontal features along the Seward Line and the occasional effects of passing slope eddies. The physical and chemical properties generally indicated upwelling over the shelf break and slope during the passing of a slope eddy; however, the upper water nutrient and chlorophyll *a* concentrations were not

always clearly affected by these phenomena. The strongest impact of a slope eddy was detected in the spring of 1999 when nutrient concentrations were clearly reduced by high phytoplankton biomass in the trailing flank of a slope eddy. This incident demonstrates the potential impact of these irregular phenomena on the productivity of the northern GOA slope waters. Due to the lack of additional shelf break and slope data in the northern GOA, the spatial extent and affect of these events in this region is still unclear. Research has found however, that these mesoscale eddies “are generated in the Alaska Current during years in which the wind forcing in the eastern GOA promotes strong downwelling along the British Columbia-Alaska coast and such wind conditions often, but not always, occur in association with ENSO events.” With this knowledge and the availability of real-time satellite data, it is possible to sample and follow these events in order to fully understand their impact on ocean productivity.

The 2001 annual cycle in PWS and over the shelf/slope revealed some general differences between these two regions. In early spring, nutrient drawdown together with a phytoplankton bloom was evident as early as April in PWS. Thereafter, phytoplankton biomass in PWS remained high through July. Over the shelf/slope, nutrient drawdown and phytoplankton growth was evident to a smaller degree in the near-shore coastal waters in April and May then reached the annual max in July. Nutrient depletion was evident in the upper waters in PWS by May, but not till July over the shelf/slope. Depleted nitrate and phosphate concentrations were present in the upper 10-20 m throughout the study area through July and August, while depleted silicate concentrations were present in the upper 20 m in PWS and in the coastal shelf waters through July and August. Nutrient concentrations were replete within and just below the upper 20 m in PWS and over the shelf/slope in July and August. In the late spring and summer, phytoplankton biomass in PWS and over the shelf/slope was higher in the subsurface waters. By late summer and fall, phytoplankton biomass was more evenly distributed across the shelf/slope and in the fall phytoplankton biomass over the shelf/slope was higher than in PWS. Nutrient ratios from the upper water column in PWS and over the shelf/slope indicated stronger silicate drawdown by a diatom dominated phytoplankton

community in the spring followed by stronger nitrate drawdown in the summer and fall. Nutrient ratios from the euphotic zone also established that the phytoplankton community over the northern GOA shelf/slope and in PWS was not limited by silicate or phosphate, but was commonly limited by nitrate. Ammonium concentrations were relatively low throughout the northern GOA throughout the seasons indicating ammonium is quickly recycled by the biological community. When higher concentrations were measured, phytoplankton biomass was higher in the subsurface coastal shelf waters and in PWS.

Data from within PWS from throughout the years and seasons revealed some general trends. In the western portion of Montague Strait, nutrient drawdown was earlier and more extensive while phytoplankton biomass was higher due to the predominant western boundary flow of the ACC. Enriched nutrient concentrations at depth in the spring compared to the shelf/slope confirmed that this semi-enclosed sea is not thoroughly flushed each year, but instead the deep waters act as a nutrient reservoir. This nutrient reservoir is also assumed to be enriched annually since nutrient enrichment was evident at depth in the spring and summer demonstrating the onshore extent of the summer flux.

Overall, the northern GOA shelf was found to be a very dynamic region with a large degree of spatial variability. The nutrient dynamics in the upper shelf/slope waters are affected by coastal inputs, flow patterns of the ACC and the Alaskan Stream, frontal features, shelf eddies such as the Kayak Eddy, passing slope eddies, and Prince William Sound. At depth, nutrient dynamics over the shelf/slope are most strongly influenced by the bathymetry and seasonal onshore flux. The northern GOA shelf/slope is a very dynamic region that requires many more years of research and monitoring to fully understand the reasons why this shelf is so biologically productive.

3.7 References

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Table 3.1 Transect occupations during GLOBEC cruises throughout 1998, 1999, 2000, and 2001. 'E' ('e') designates those cruises that likely involved the presence of a large, slow (small, fast) eddy over the slope according to the ground track D89 data.

	northern GOA shelf											PWS			
	GAK	CF	HE	AHC	CCSE	RI	CC	CCSW	PWSW	CR	CS	HB	MS	KIP	PWS
Mar-98	x	x					x								
Apr-98	x	x					x	x					x	x	
May-98	x			x											
Jul-98	x	x		x			x	x	x				x	x	
Oct-98	x	x													
Dec-98	x (e)	x		x											
Mar-99	x (E)	x											x	x	
Apr-99	x (E)	x				x	x					x	x	x	
May-99	x (E)	x				x						x	x	x	
Aug-99	x (E)	x		x		x	x	x	x				x	x	
Oct-99	x (E)	x					x	x	x				x	x	
Dec-99	x (e)	x	x	x		x					x	x	x	x	
Mar-00	x	x	x	x								x	x	x	
Apr-00	x (e)	x											x	x	
May-00	x	x	x	x		x	x			x		x	x	x	x
Aug-00	x (E)	x	x	x								x	x	x	
Oct-00	x (E)	x										x	x	x	
Dec-00	x	x	x			x						x	x	x	
Mar-01	x	x	x									x	x	x	x
Apr-01	x	x	x	x	x							x	x	x	x
May-01	x (E)	x	x	x	x							x	x	x	x
Jul-01	x (E)	x	x	x	x	x						x	x	x	x
Aug-01	x	x	x	x	x				x			x	x	x	x
Oct-01	x	x										x	x	x	x
Dec-01	x	x	x						x			x	x	x	x

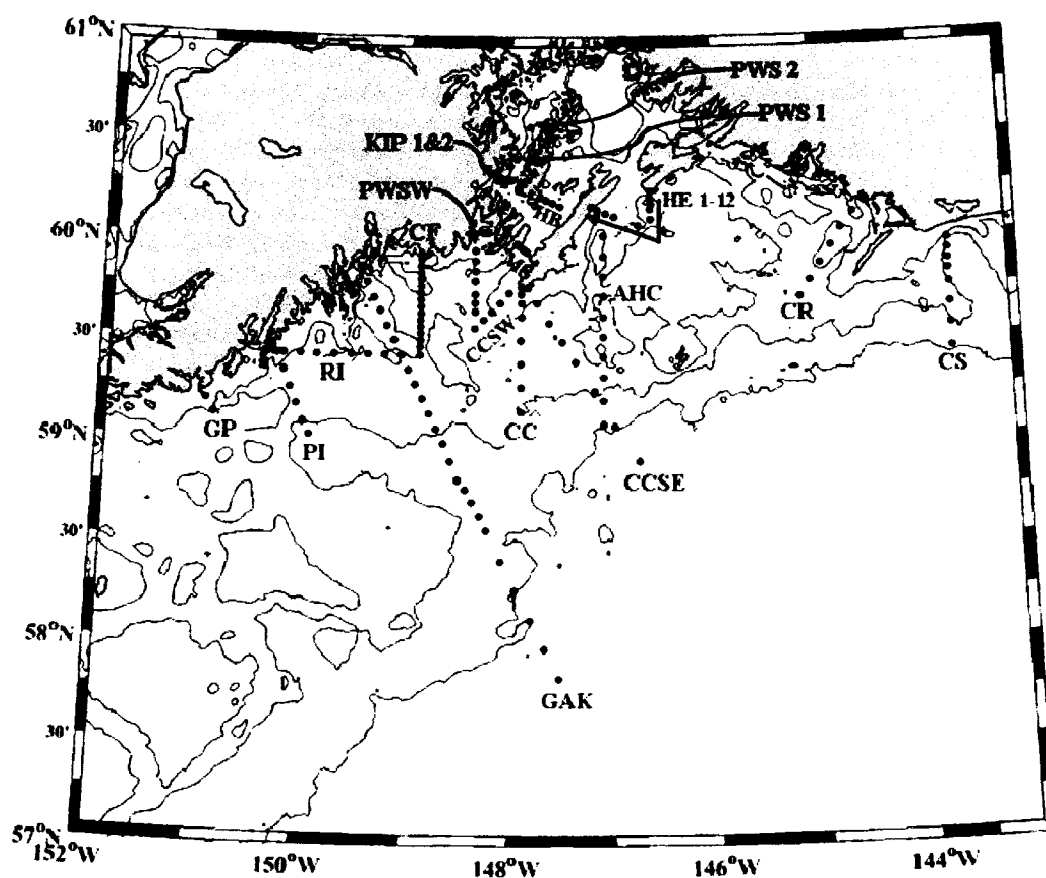


Figure 3.1 The GLOBEC transects with station number increasing with distance offshore over the shelf/slope, except for the HE stations which increase along the arrow. The individual Prince William Sound stations are labeled and the stations along HB and MS increase from northwest to southeast.

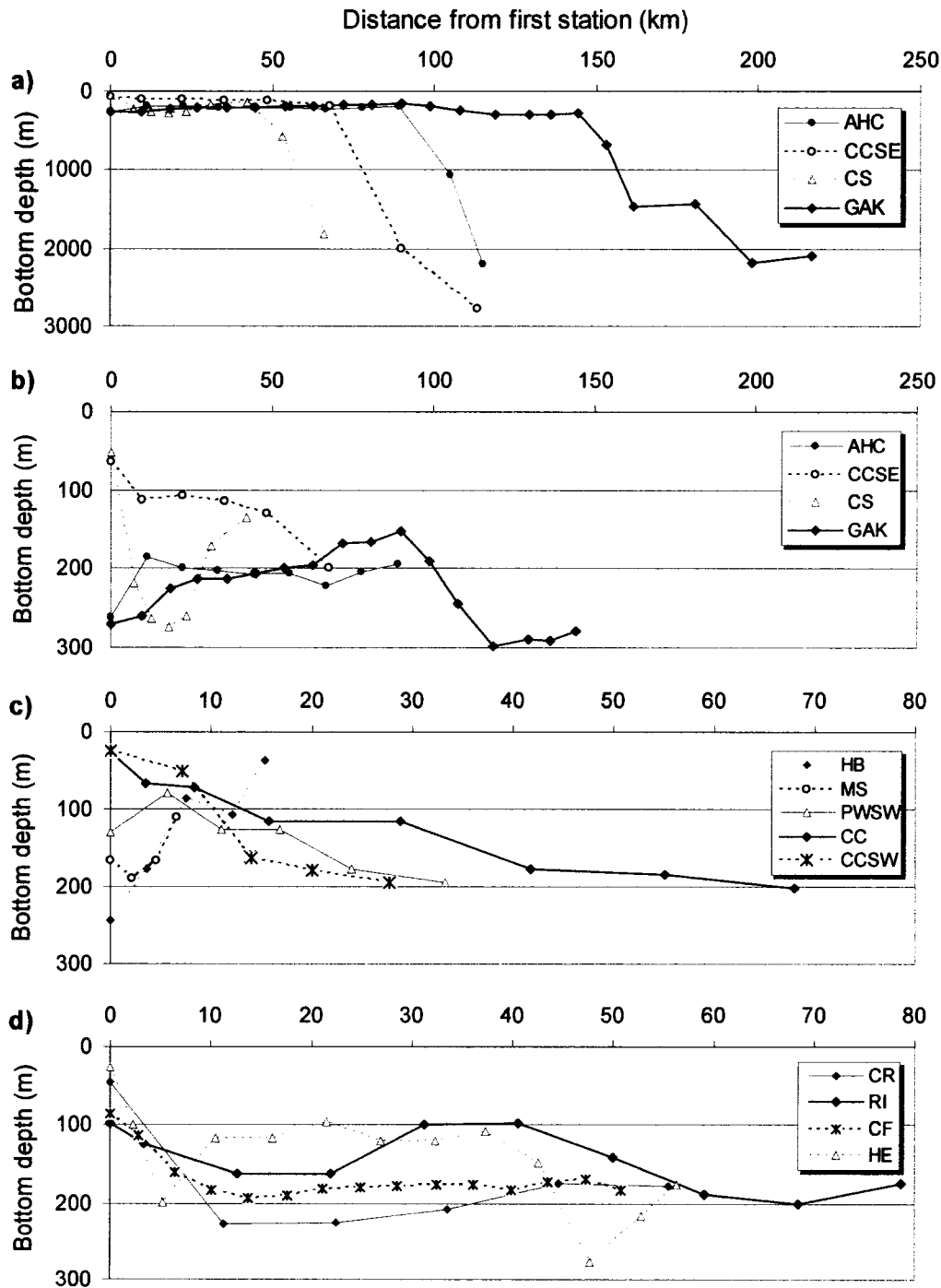


Figure 3.2 Cross-shelf bathymetries along (a) AHC, CCSE, CS, and GAK full scale and (b) stations shallower than 300 m (c) HB, MS, PWSW, CC, and CCSW and (d) CR, RI, CF, and HE from near-shore to off-shore.

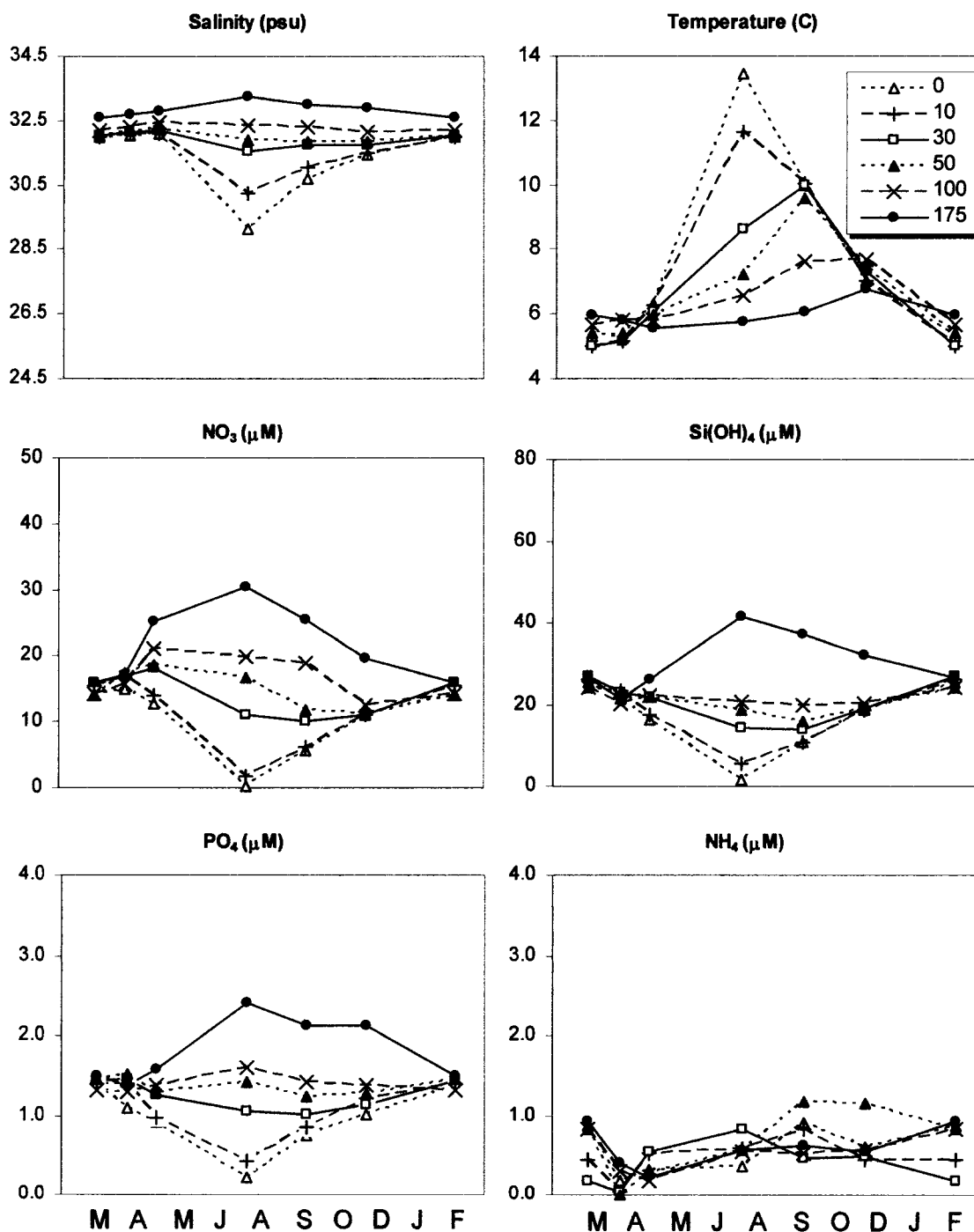


Figure 3.3 Averaged annual cycle of salinity, temperature, nitrate, silicate, phosphate and ammonium at CF 7.

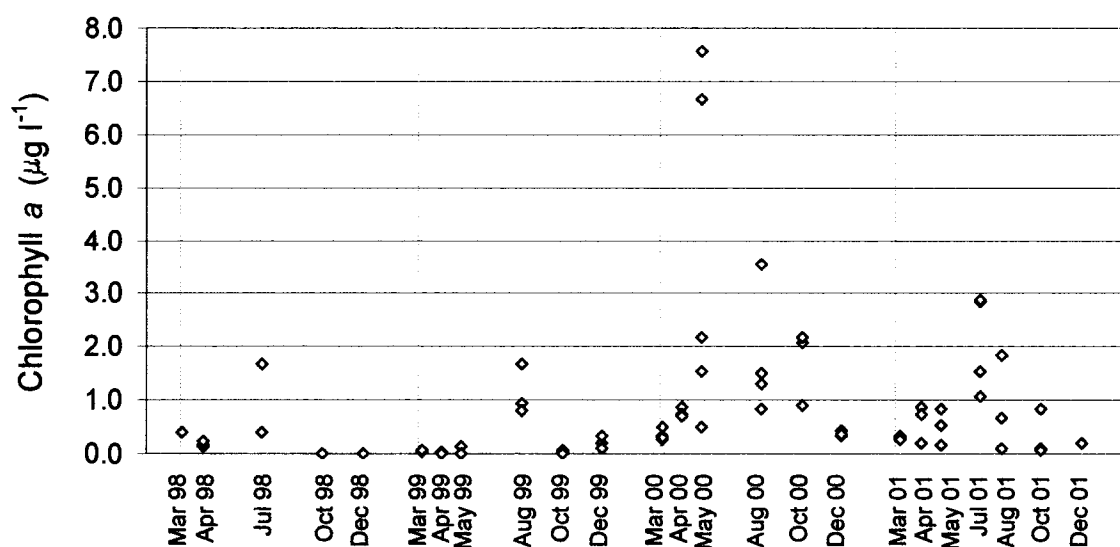


Figure 3.4 Time series at CF 7 of chlorophyll *a* concentrations from the upper 50 m March 1998 – December 2001. Dashed lines indicate March data.

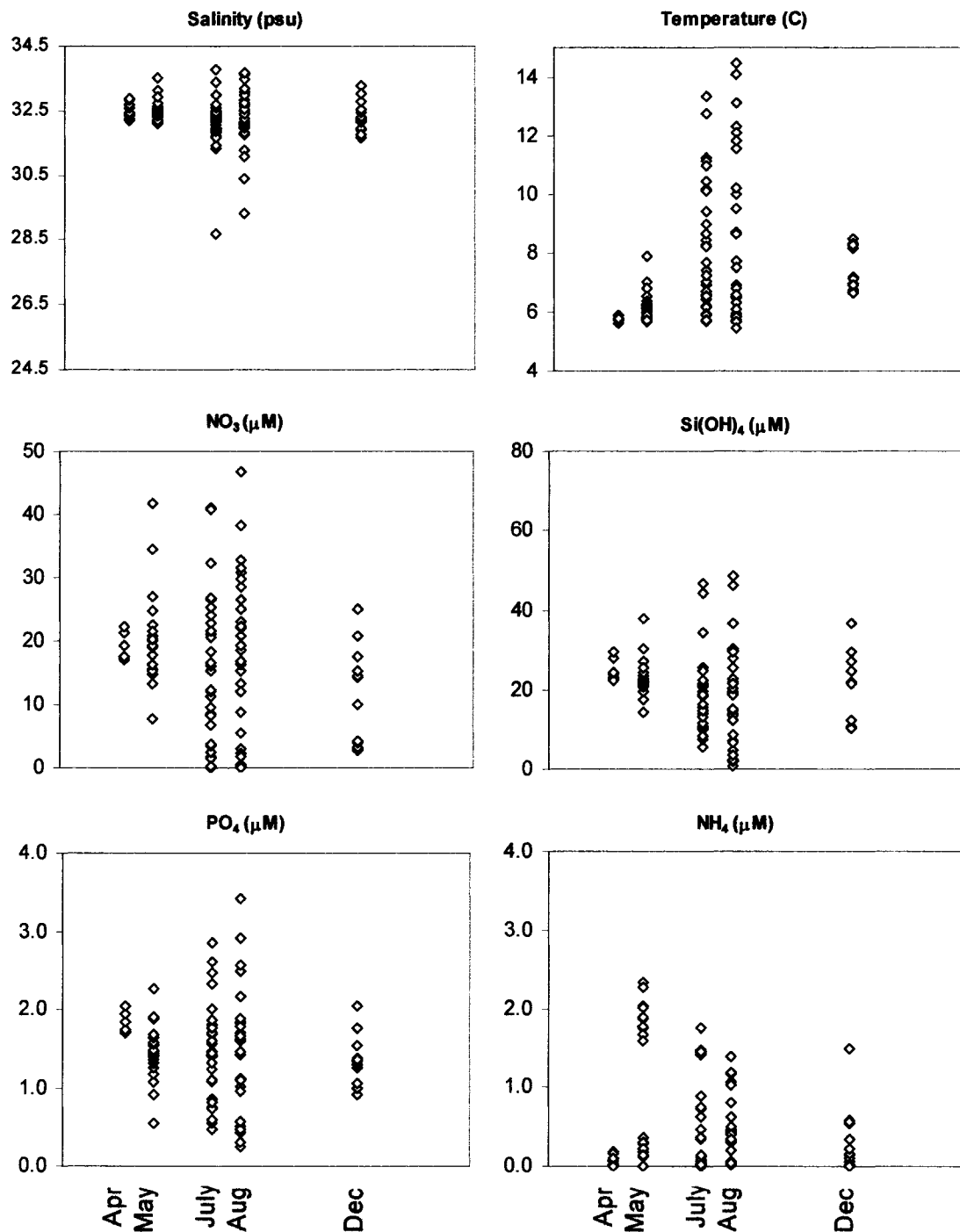


Figure 3.5 Collective annual cycles of salinity, temperature, nitrate, silicate, phosphate and ammonium at AHC 5.

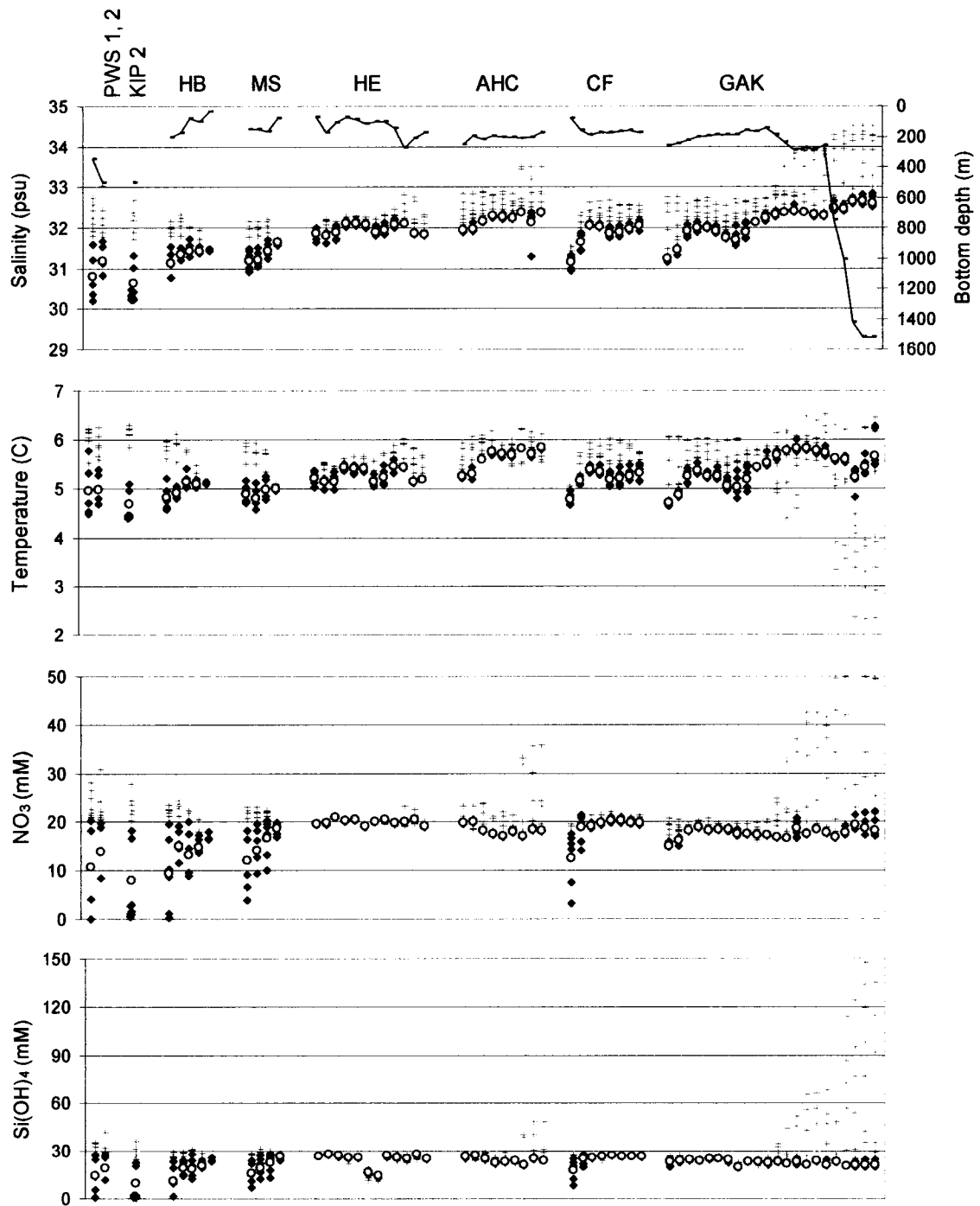


Figure 3.6 Scatter plots of salinity, bottom depth, temperature, nitrate, and silicate data collected from PWS and the northern GOA in April 2001. (+ = data > 50 m, ◆ = data < 50 m, and ○ = upper 50 m means)

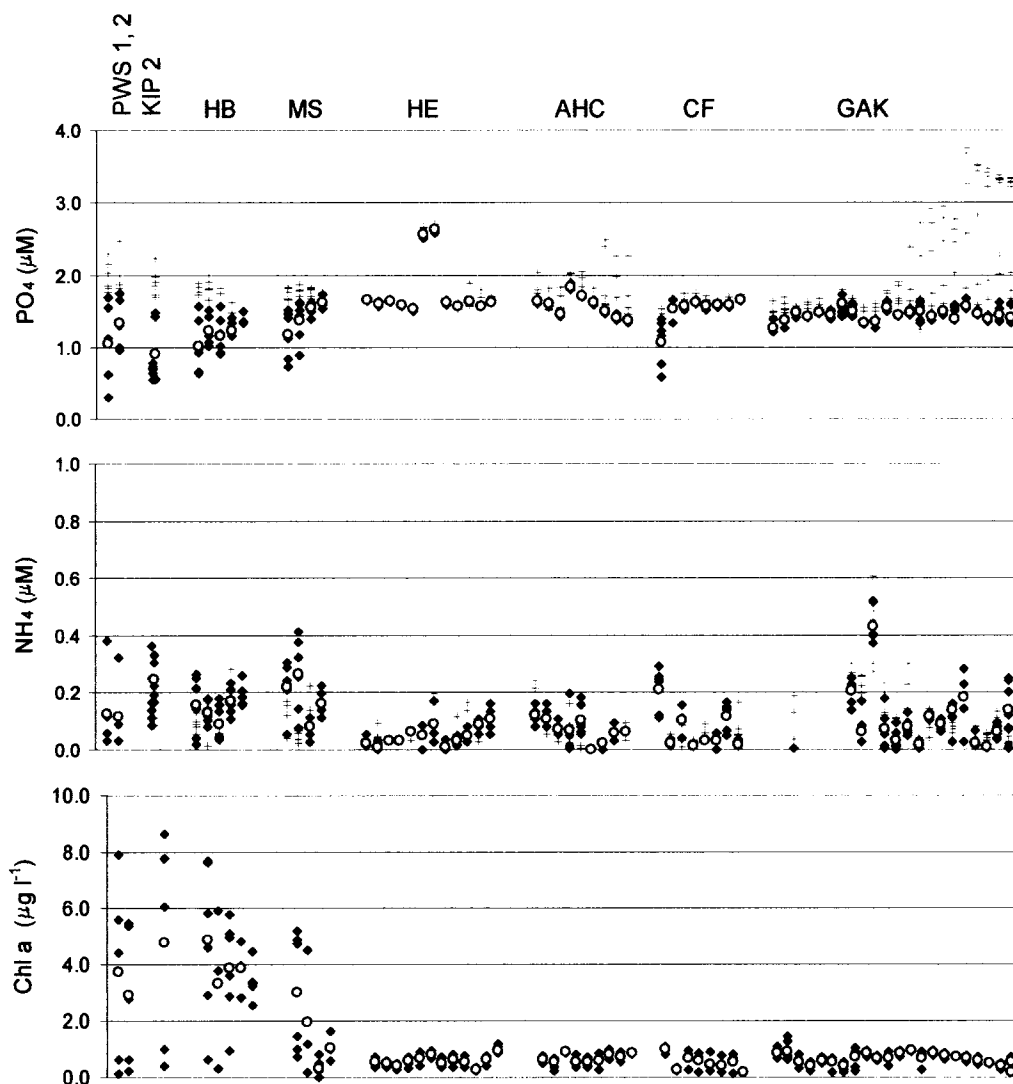


Figure 3.6 (continued) Scatter plots of phosphate, ammonium, and chl *a* data collected from PWS and the northern GOA in April 2001. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

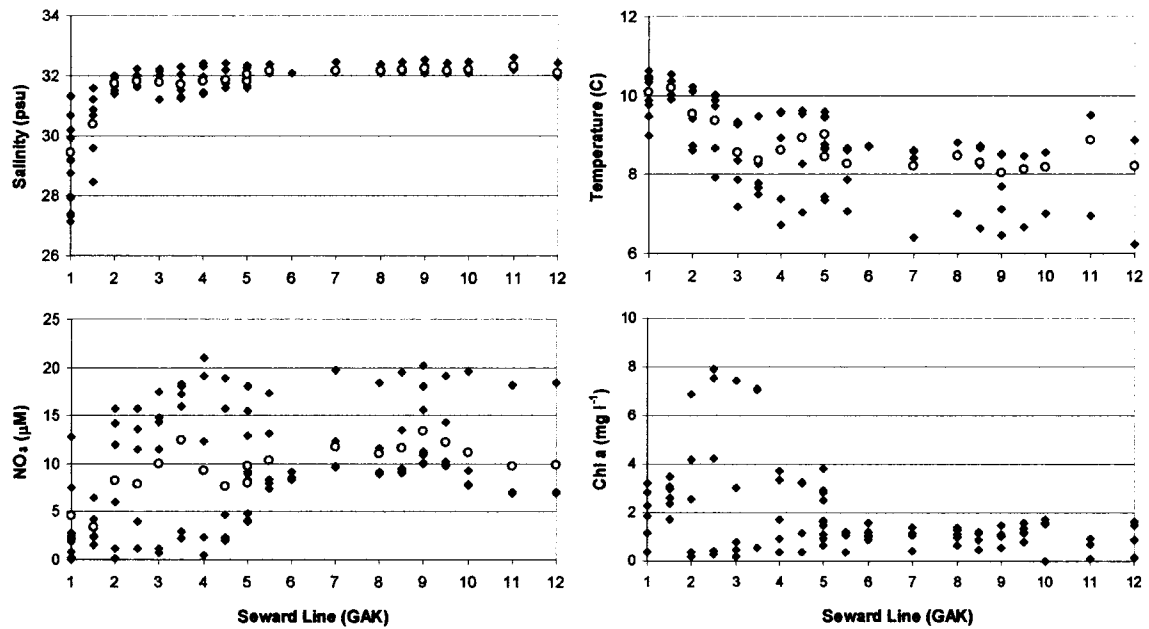


Figure 3.7 Scatter plots of salinity, temperature, nitrate, and chl *a* data (♦) and means (○) collected from the upper 50 m along the Seward Line (GAK 1-12) in October 2000.

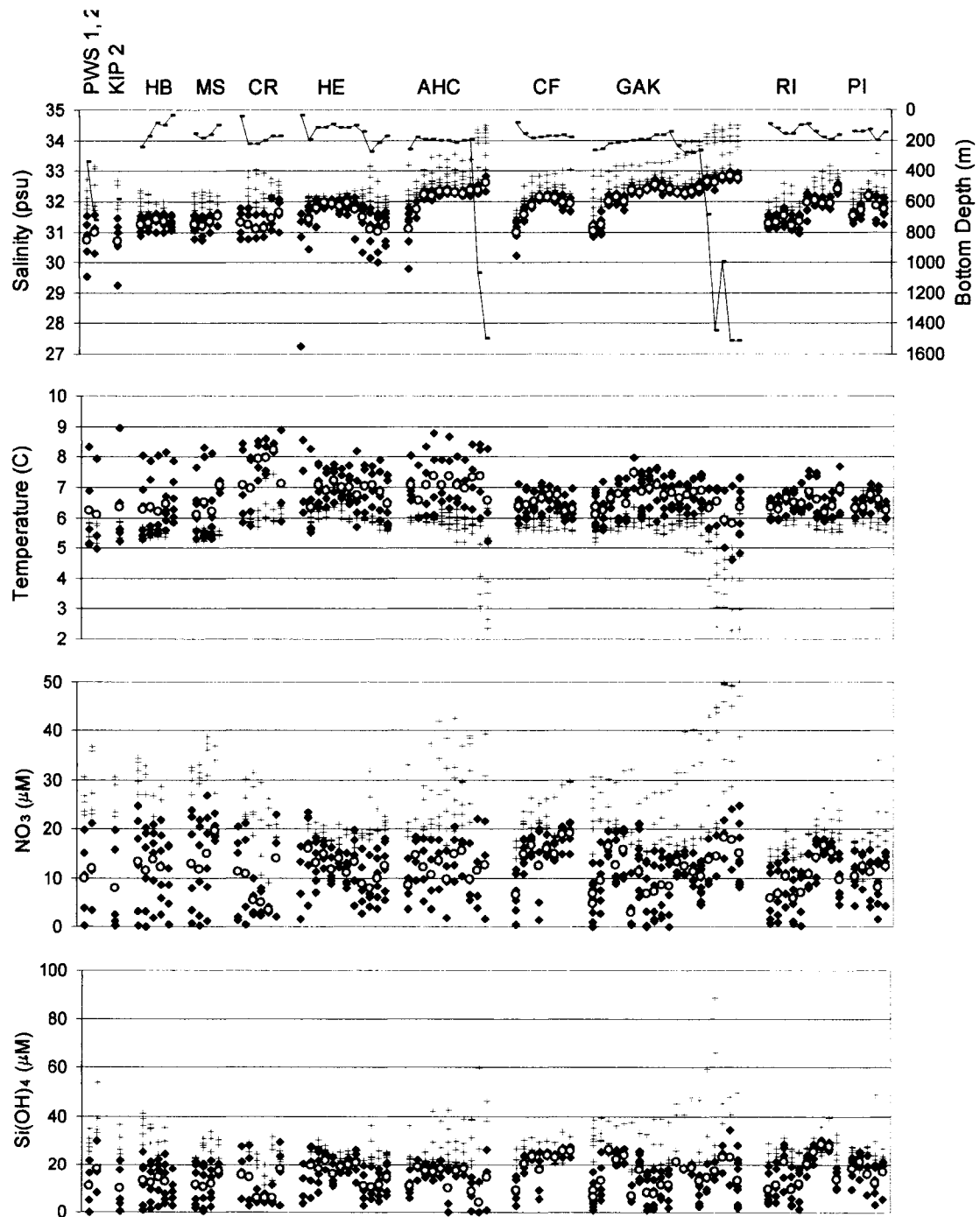


Figure 3.8 Scatter plots of salinity, bottom depth, temperature, nitrate, and silicate data collected from PWS and the northern GOA in May 2000. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

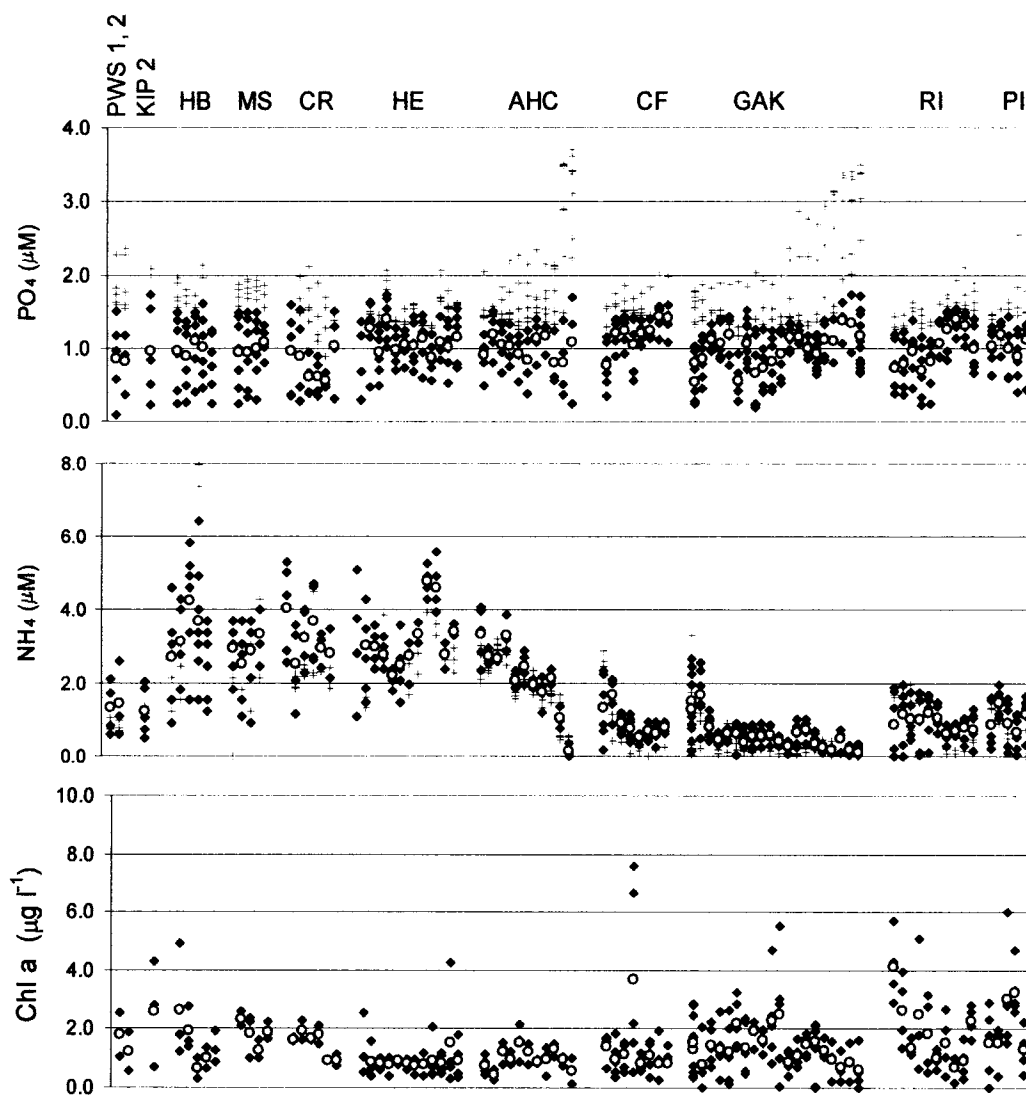


Figure 3.8 (continued) Scatter plots of phosphate, ammonium, and chl *a* data collected from PWS and the northern GOA in May 2000. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

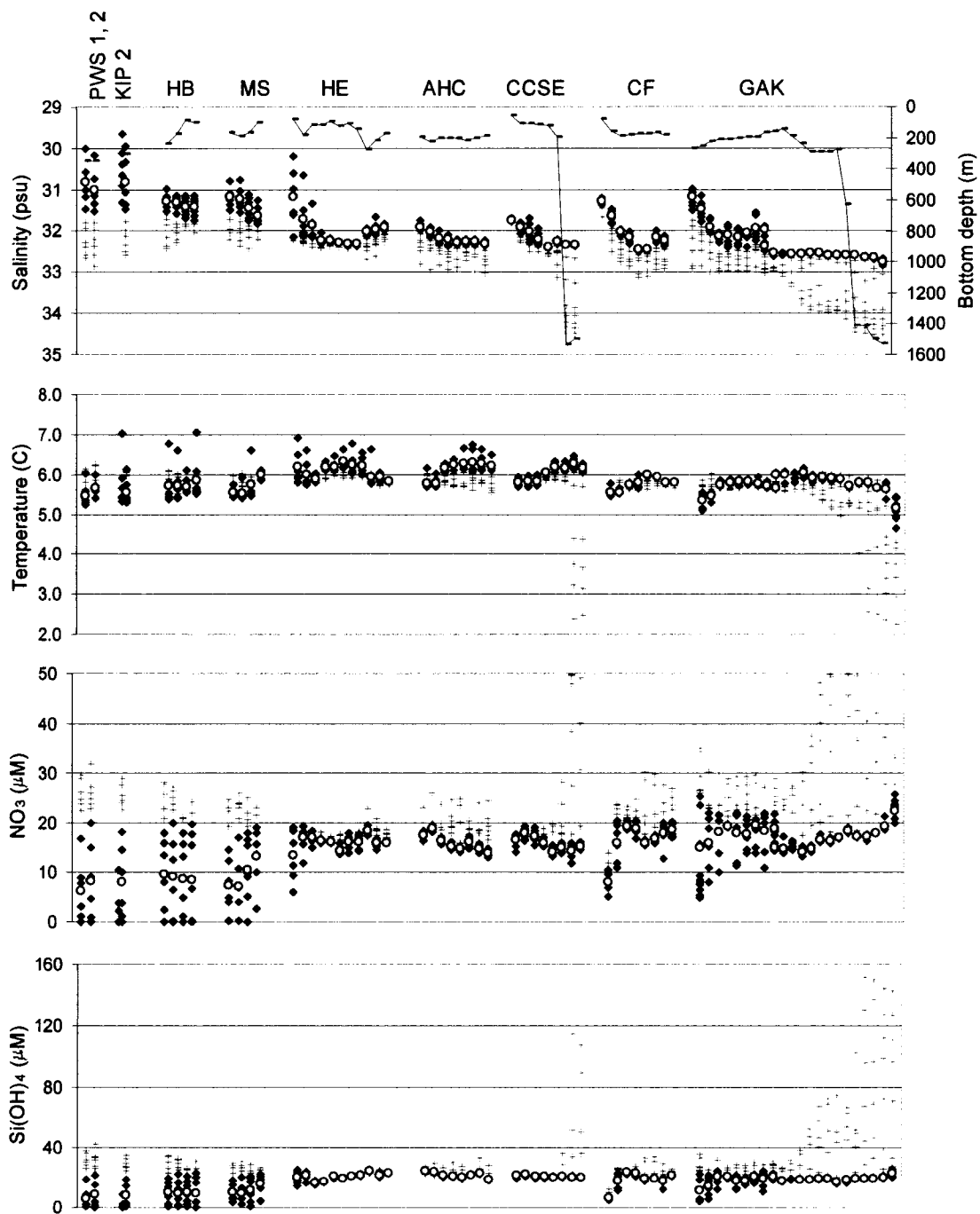


Figure 3.9 Scatter plots of salinity, bottom depth, temperature, nitrate, and silicate data collected from PWS and the northern GOA in May 2001. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

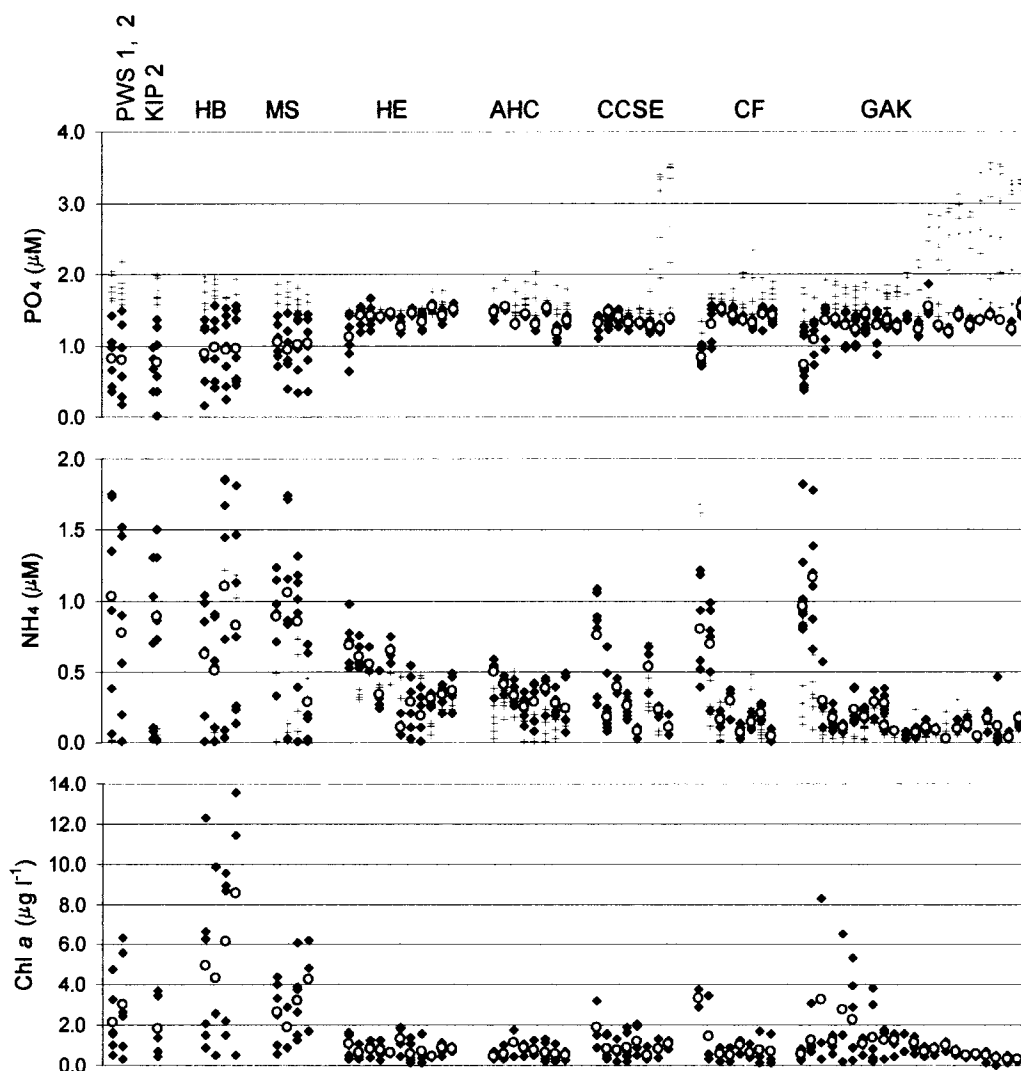


Figure 3.9 (continued) Scatter plots of phosphate, ammonium, and chl *a* data collected from PWS and the northern GOA in May 2001. (+ = data > 50 m, ♦ = data < 50 m, and ○ = upper 50 m means)

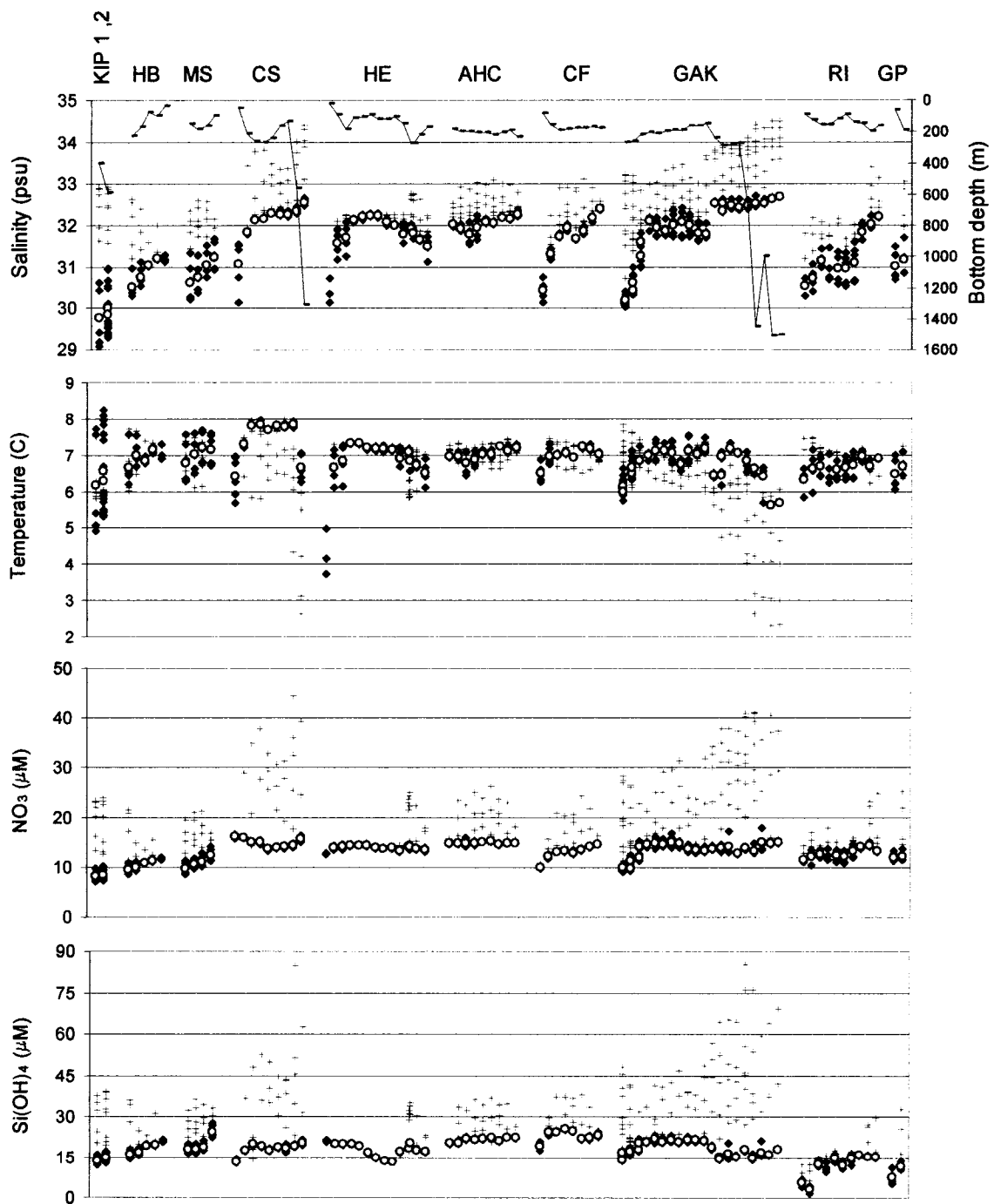


Figure 3.10 Scatter plots of salinity, bottom depth, temperature, nitrate, and silicate, data collected from PWS and the northern GOA in December 1999. (+ = data > 50 m, ◆ = data < 50 m, and ○ = upper 50 m means)

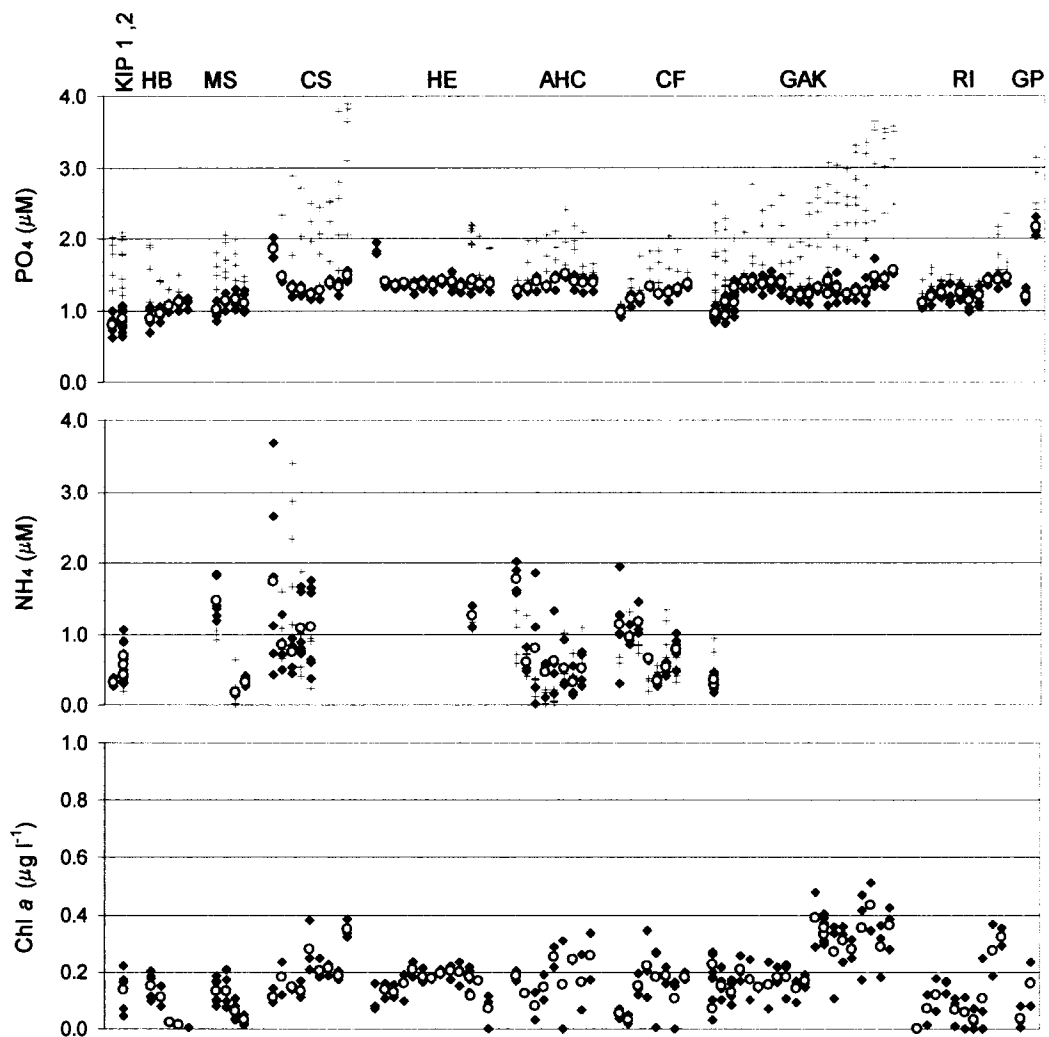


Figure 3.10 (continued) Scatter plots phosphate, ammonium, and chl *a* data collected from PWS and the northern GOA in December 1999. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

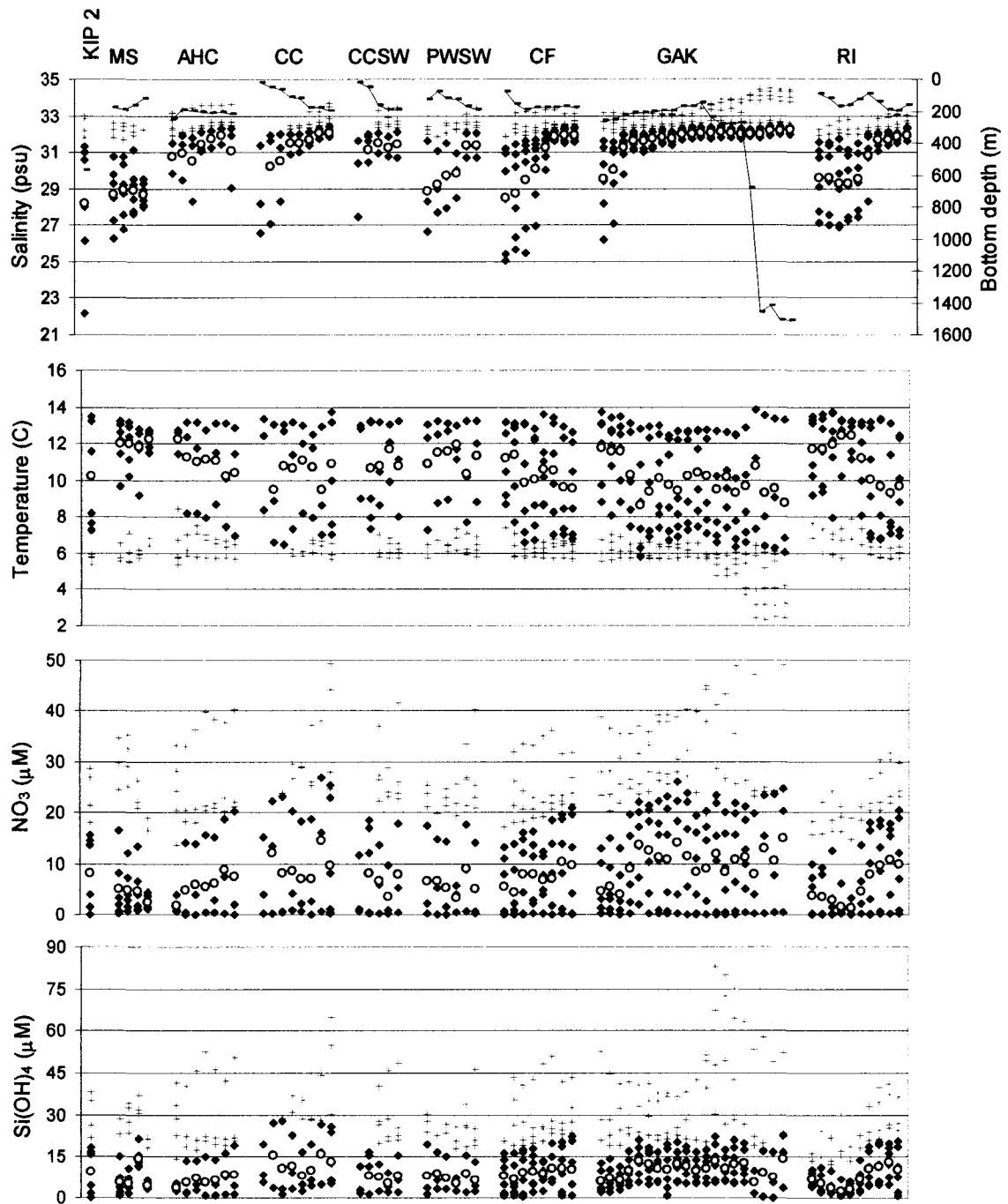


Figure 3.11 Scatter plots of salinity, bottom depth, temperature, nitrate, and silicate data collected from PWS and the northern GOA in August 1999. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

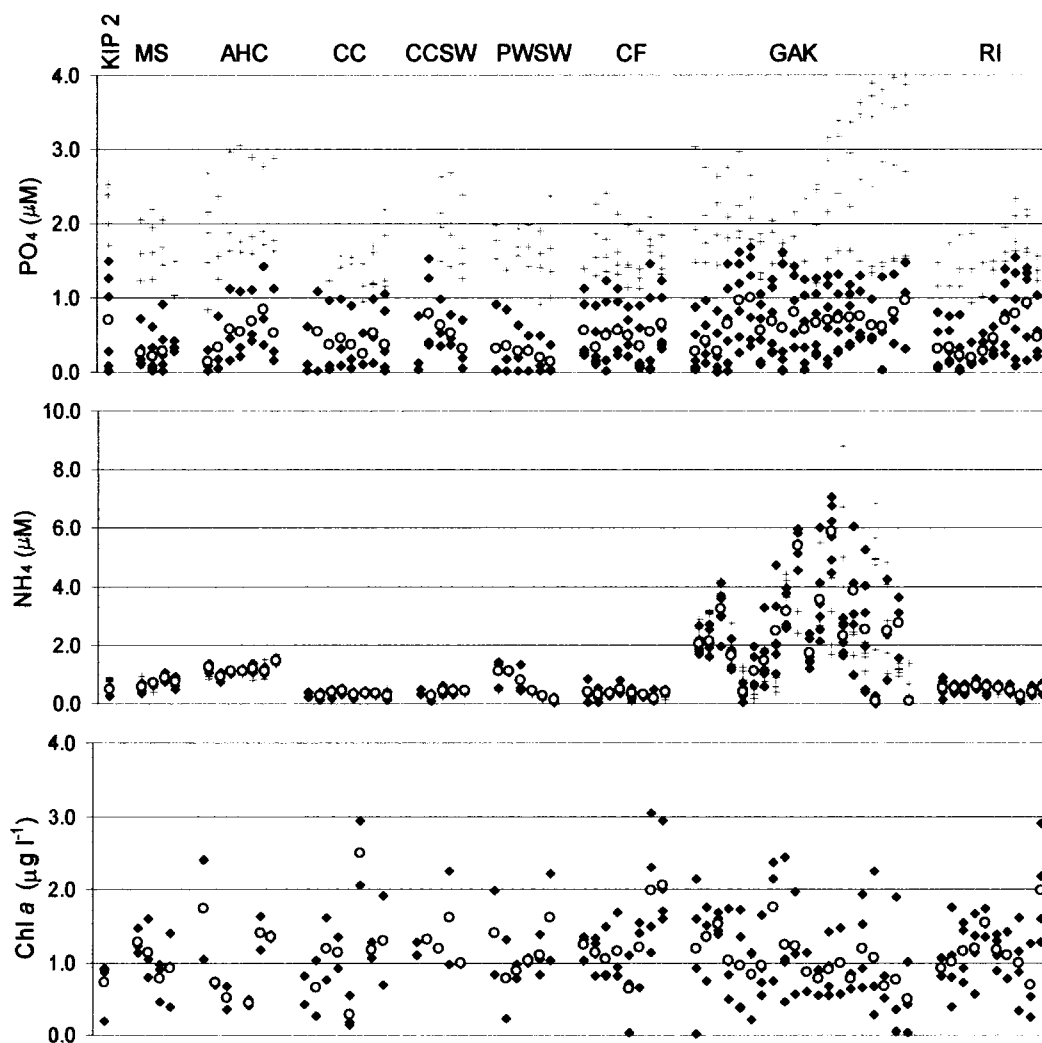


Figure 3.11 (continued) Scatter plots of phosphate, ammonium, and chl *a* data collected from PWS and the northern GOA in August 1999. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

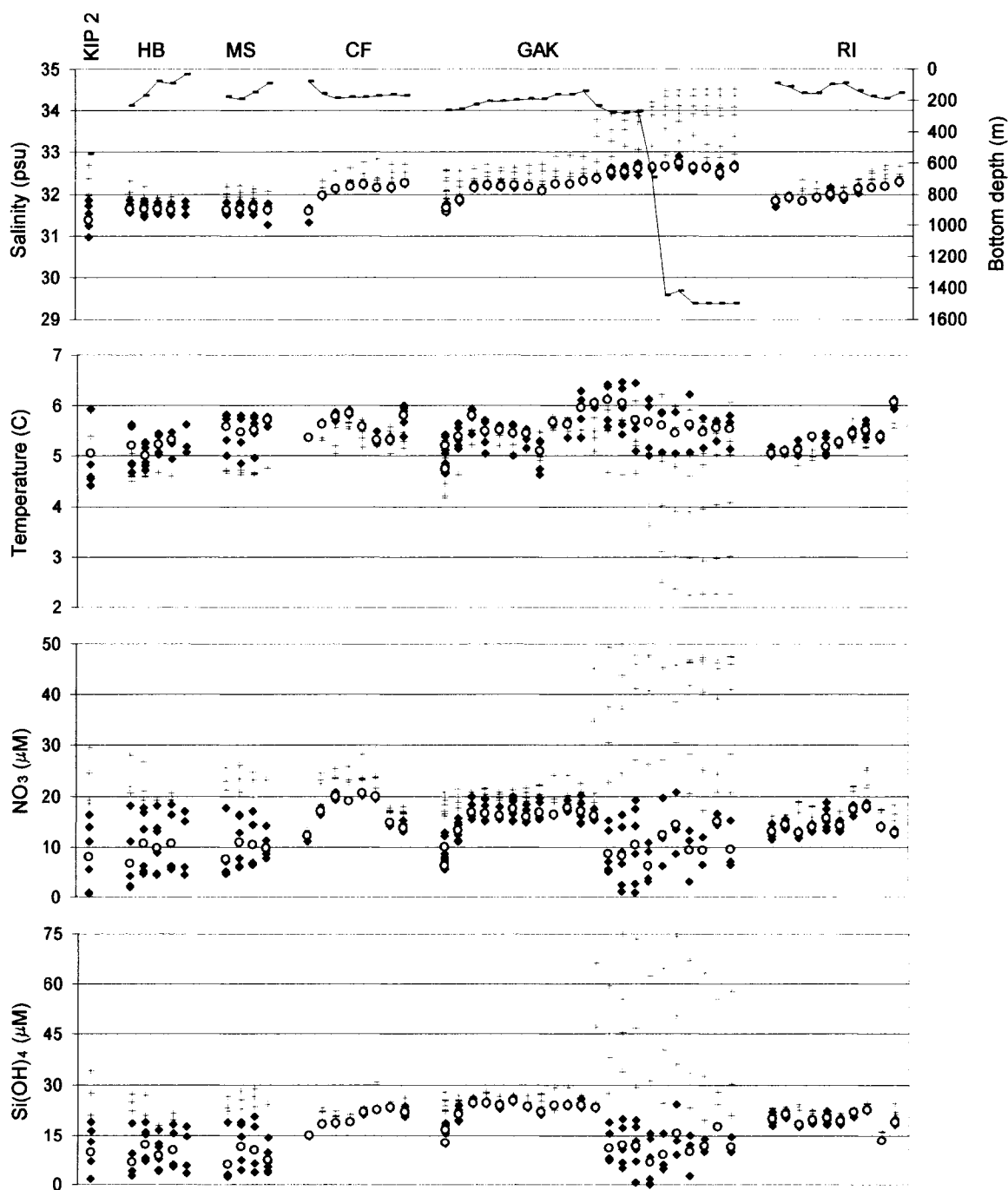


Figure 3.12 Scatter plots of salinity, bottom depth, temperature, nitrate, and silicate data collected from PWS and the northern GOA in May 1999. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

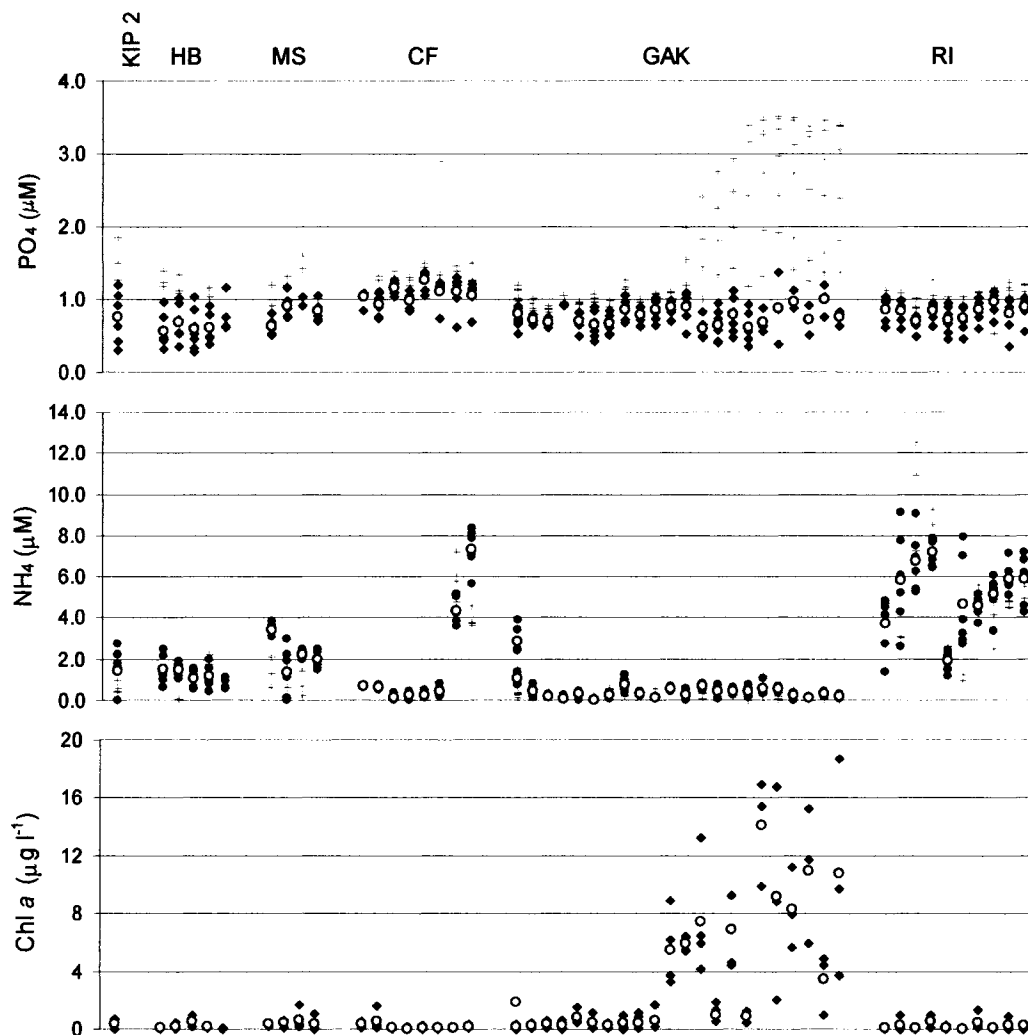


Figure 3.12 (continued) Scatter plots of phosphate, ammonium, and chl *a* data collected from PWS and the northern GOA in May 1999. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

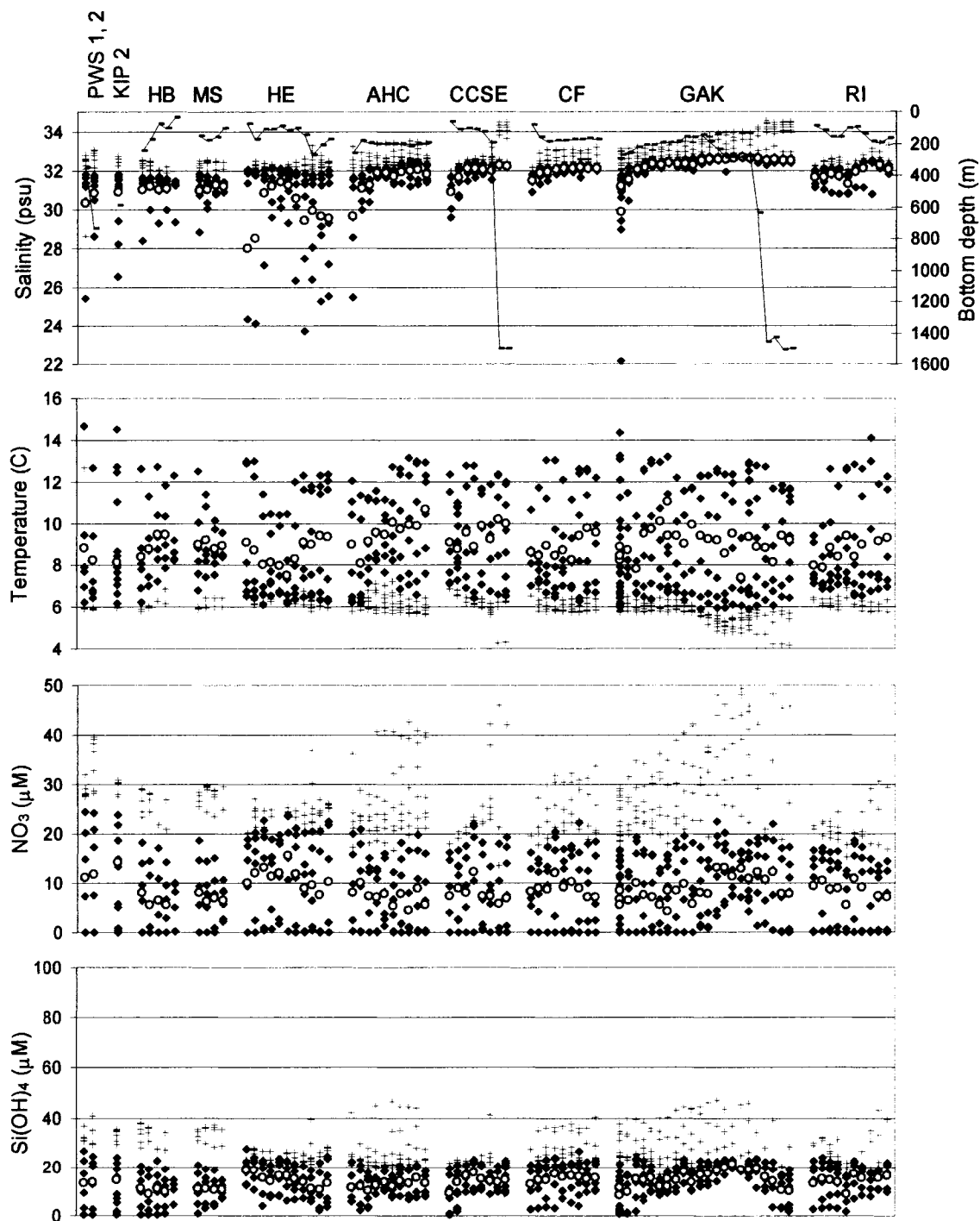


Figure 3.13 Scatter plots of salinity, bottom depth, temperature, nitrate, and silicate data collected from PWS and the northern GOA in July 2001. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

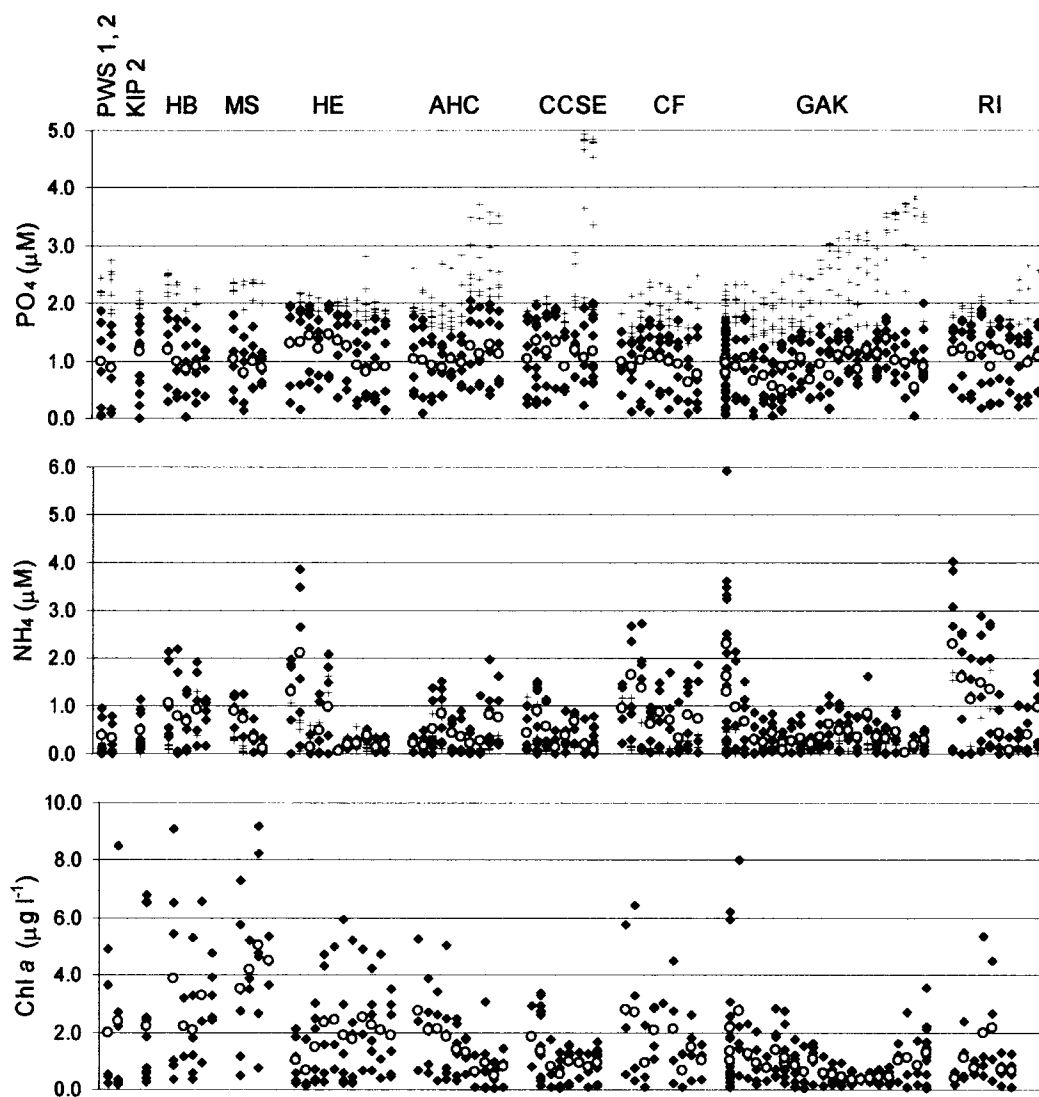


Figure 3.13 (continued) Scatter plots of phosphate, ammonium, and chl *a* data collected from PWS and the northern GOA in July 2001. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

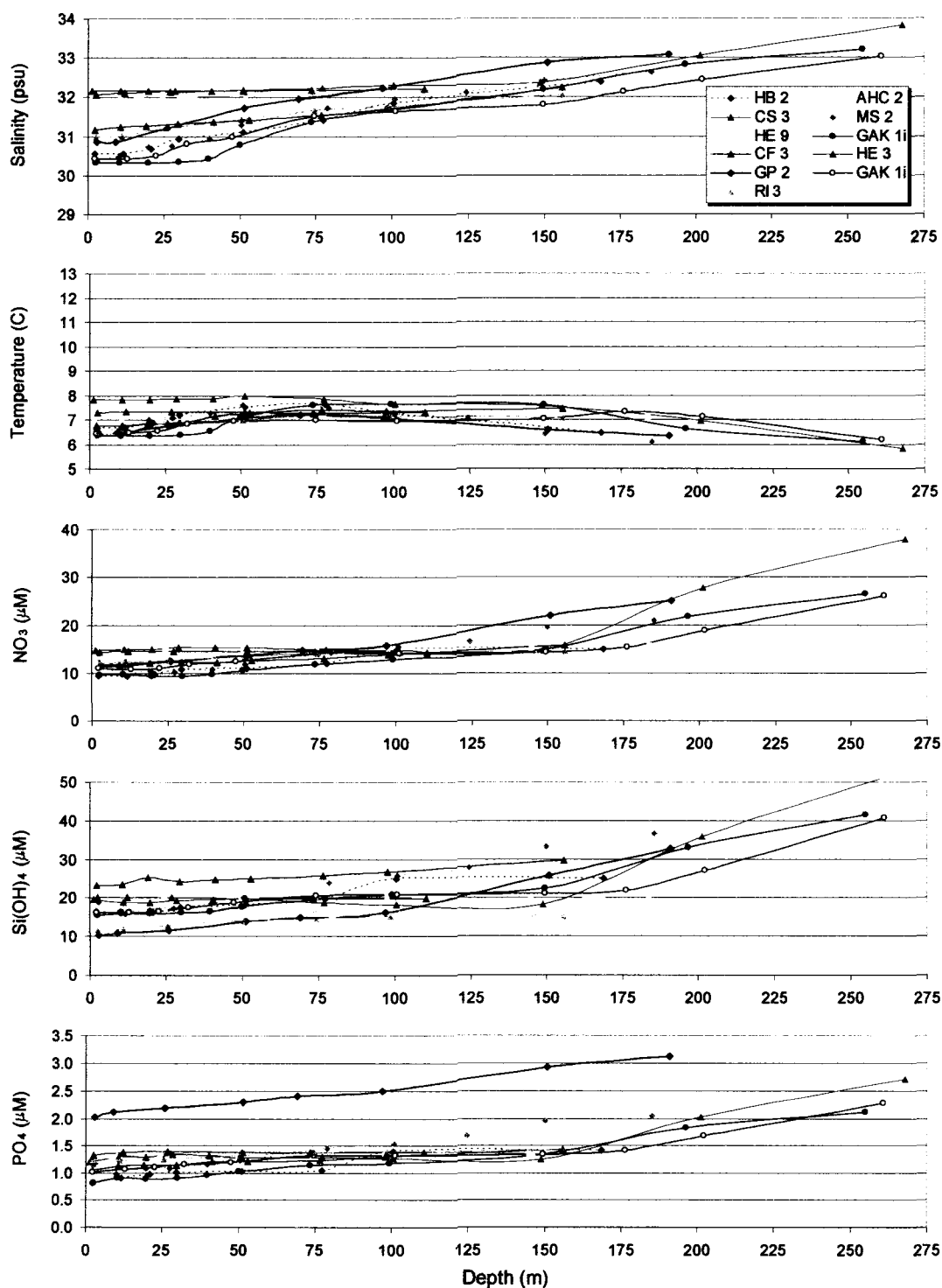


Figure 3.14 Profiles of salinity, temperature, nitrate, silicate, and phosphate collected from near shore northern GOA stations in December 1999.

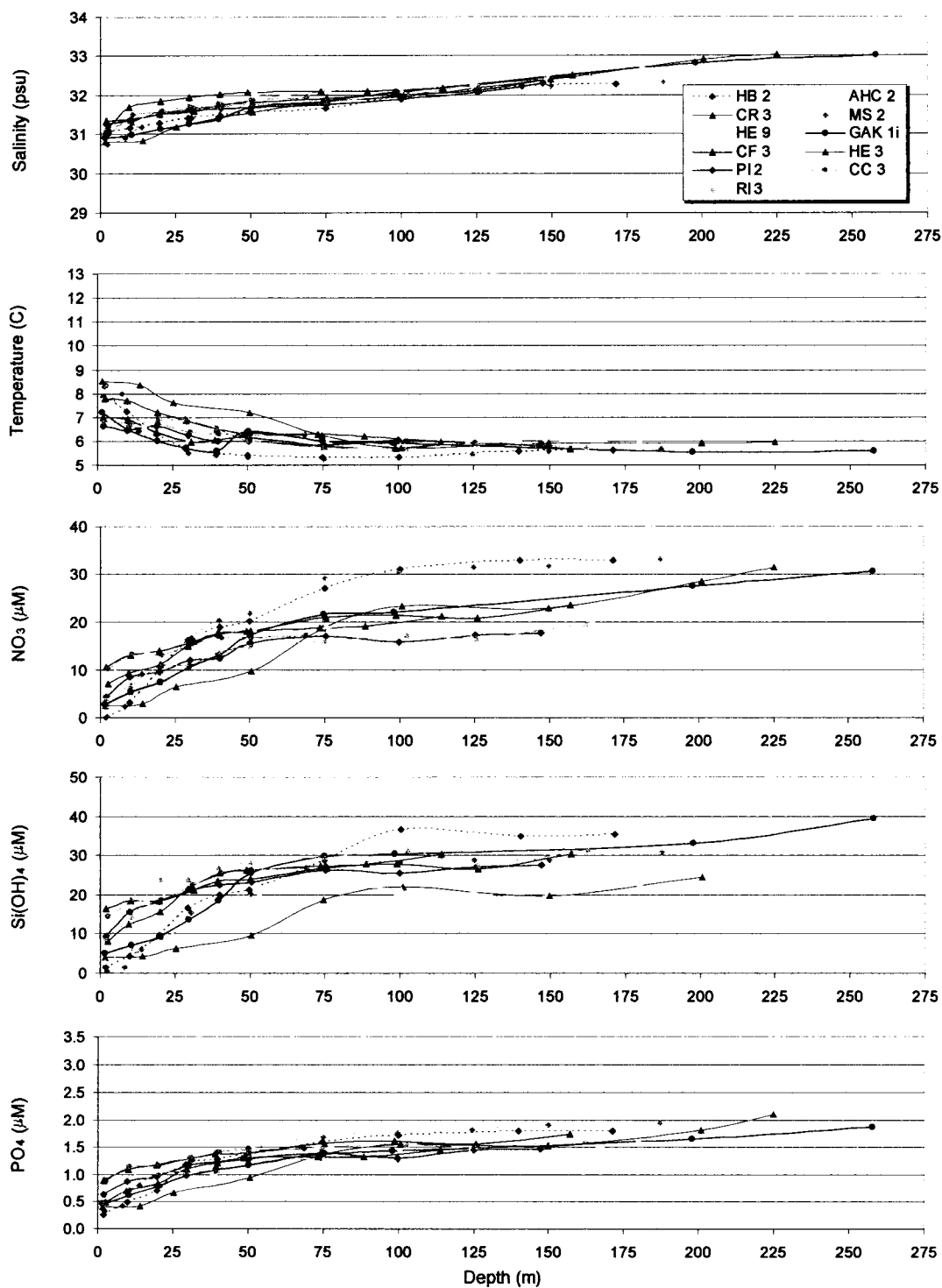


Figure 3.15 Profiles of salinity, temperature, nitrate, silicate, and phosphate collected from near shore northern GOA stations in May 2000.

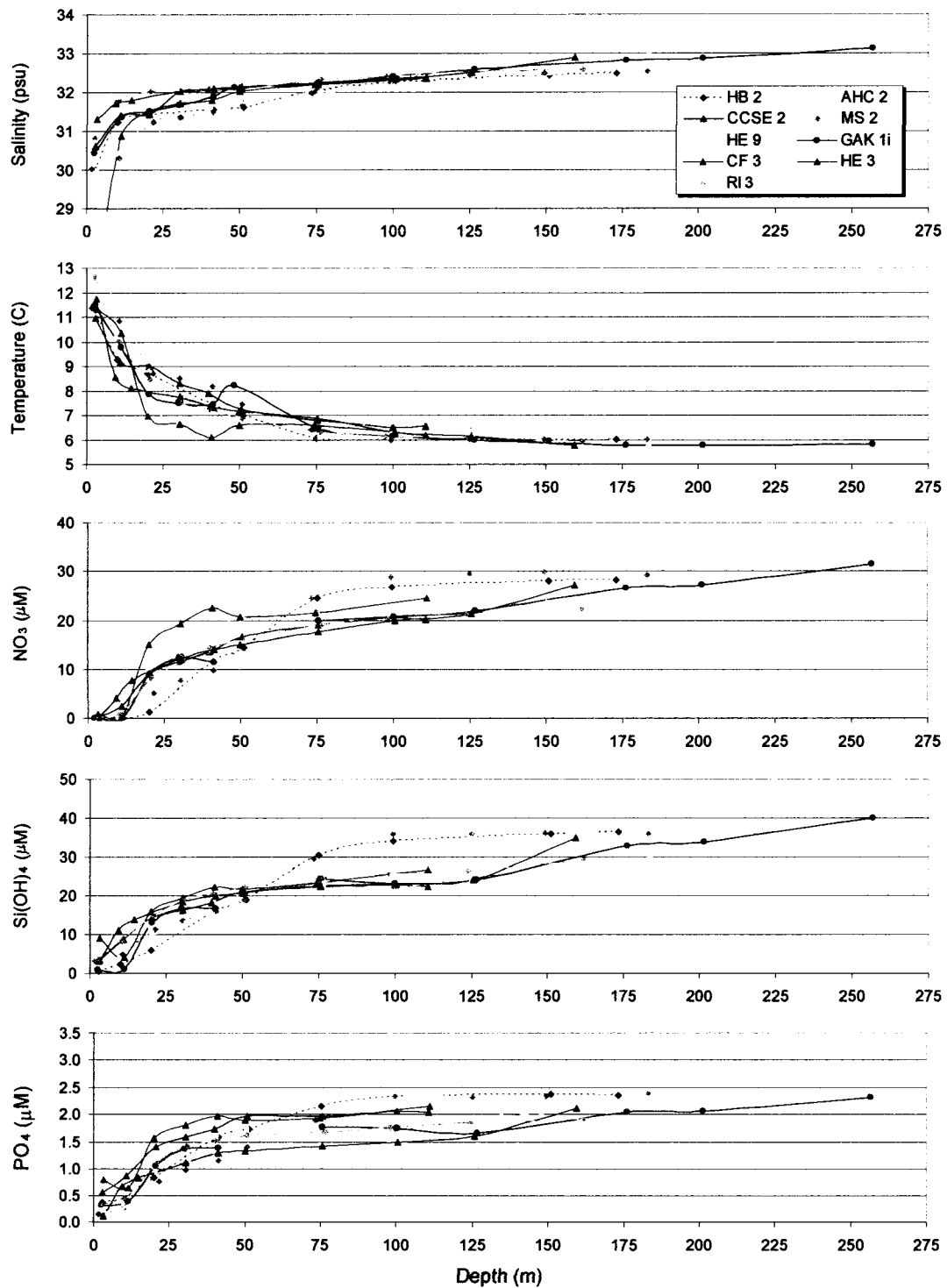


Figure 3.16 Profiles of salinity, temperature, nitrate, silicate, and phosphate collected from near shore northern GOA stations in July 2001.

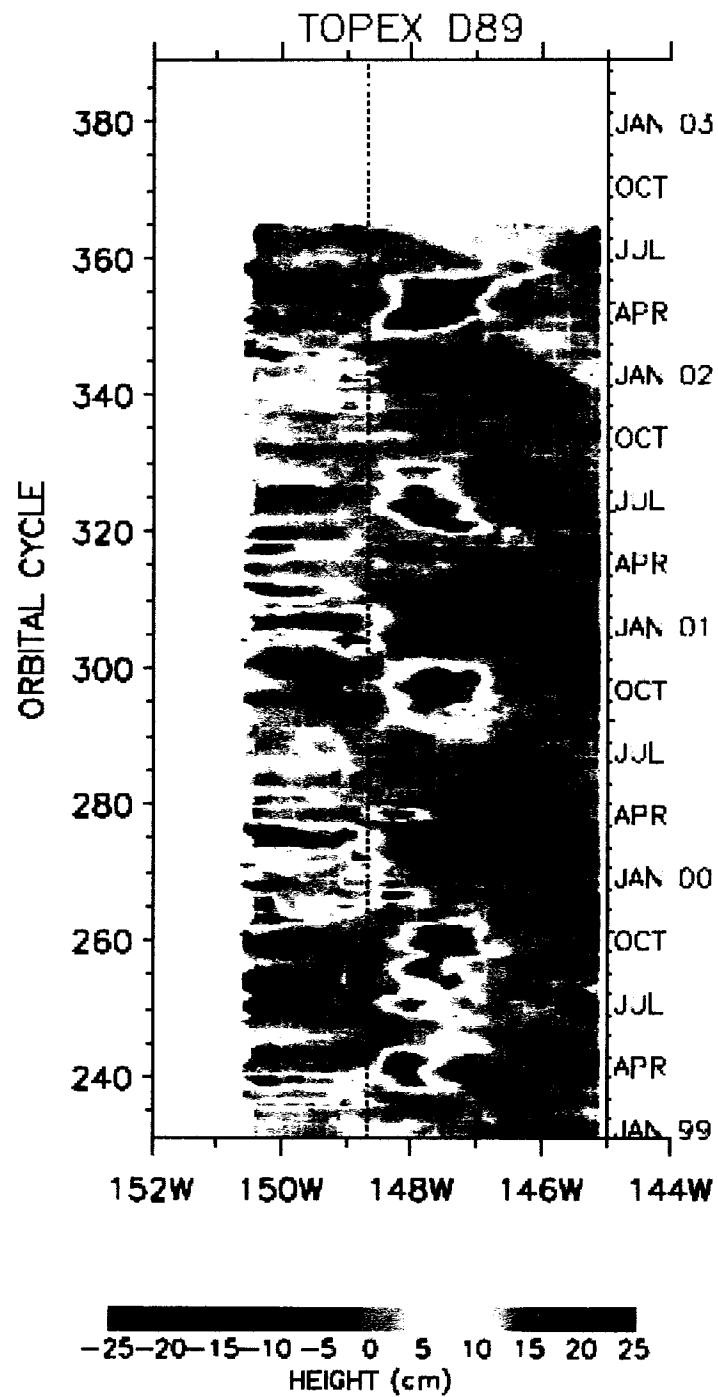


Figure 3.17 SSHA along ground track D89 January 1999 – August 2002.

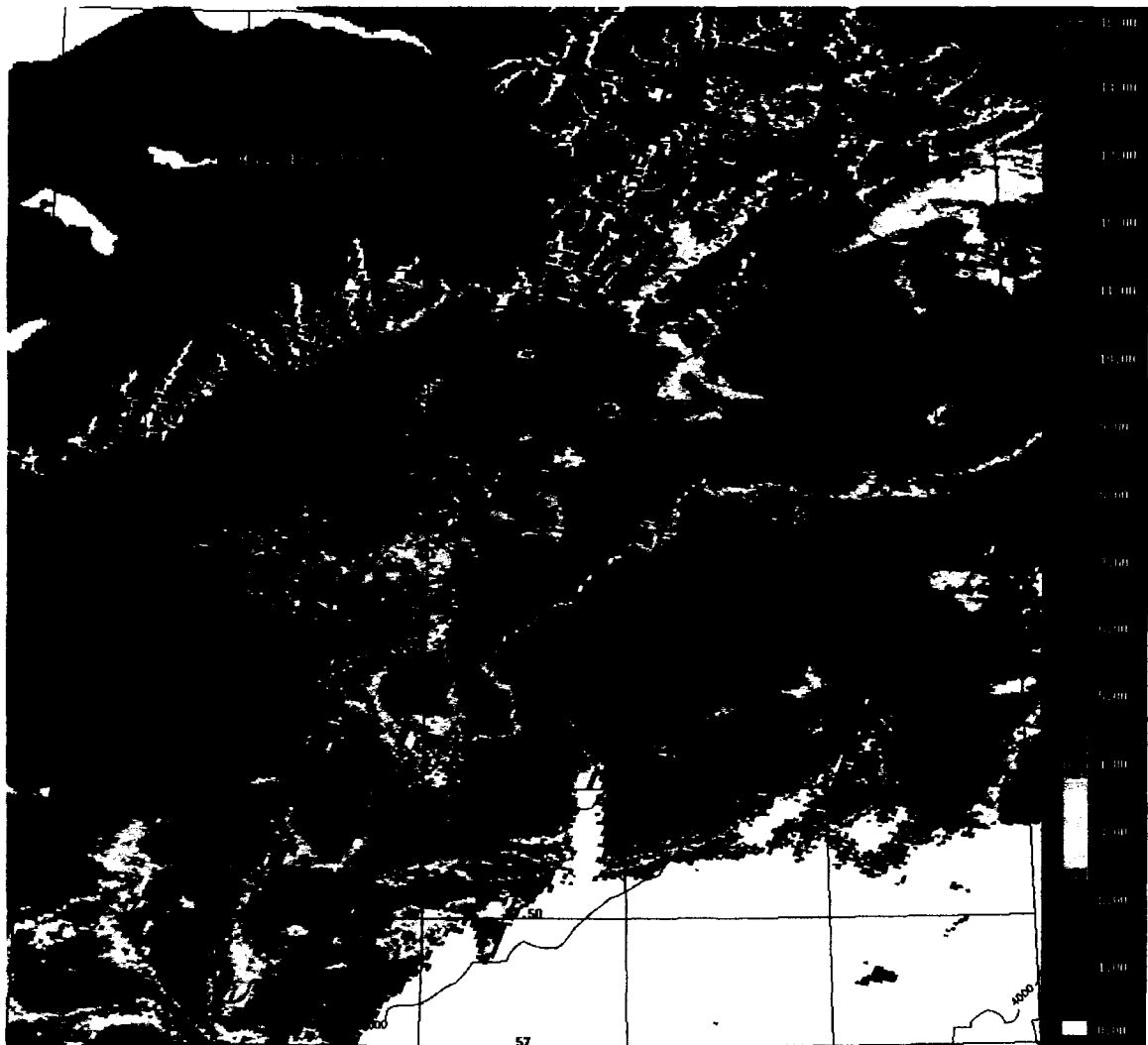


Figure 3.18 SeaWiFS image taken May 15th, 1999.

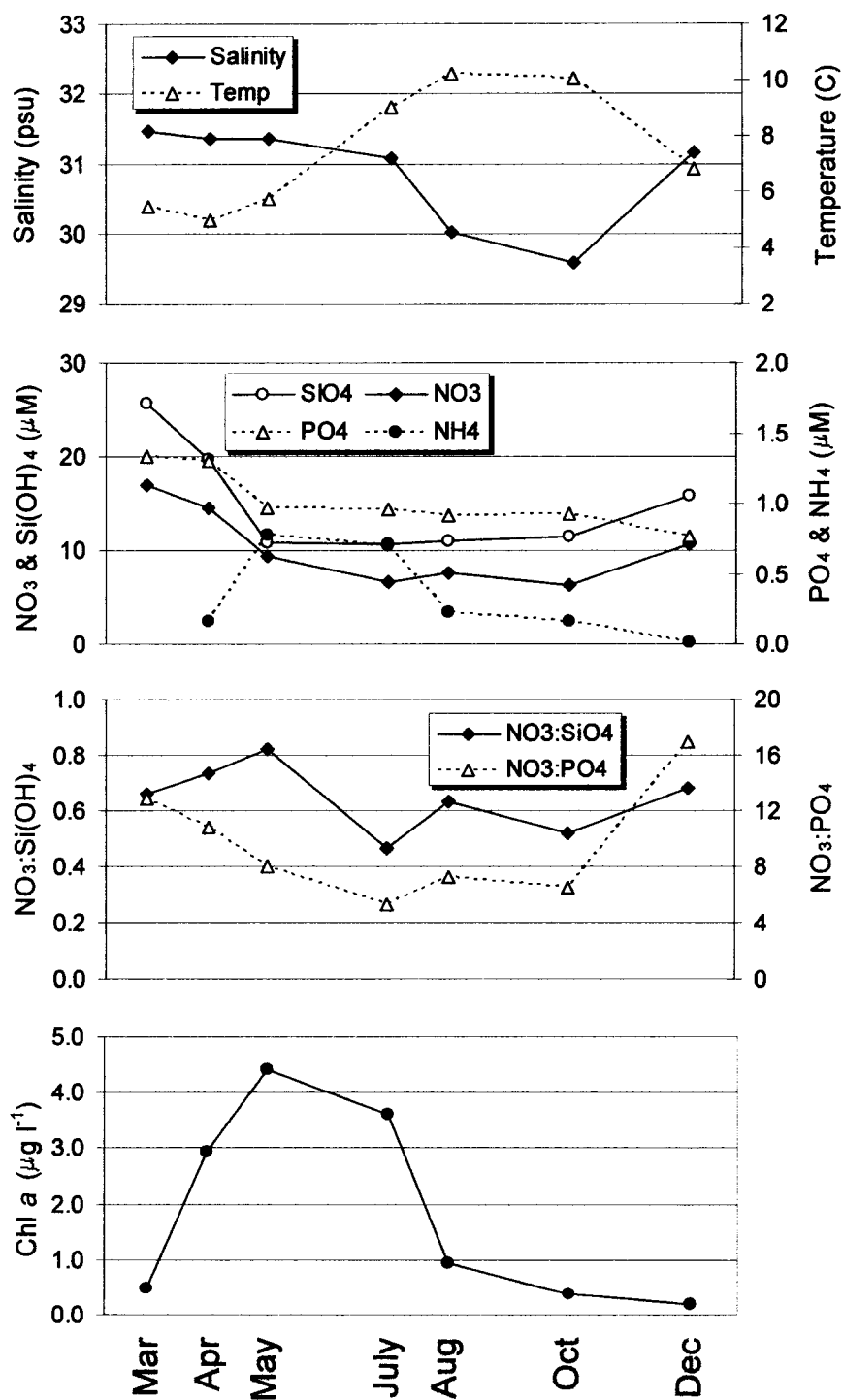


Figure 3.19 The 2001 annual cycle in PWS from the upper 50 m means of salinity, temperature, nitrate, silicate, phosphate, ammonium, N:Si ratios, N:P ratios, and chl *a*.

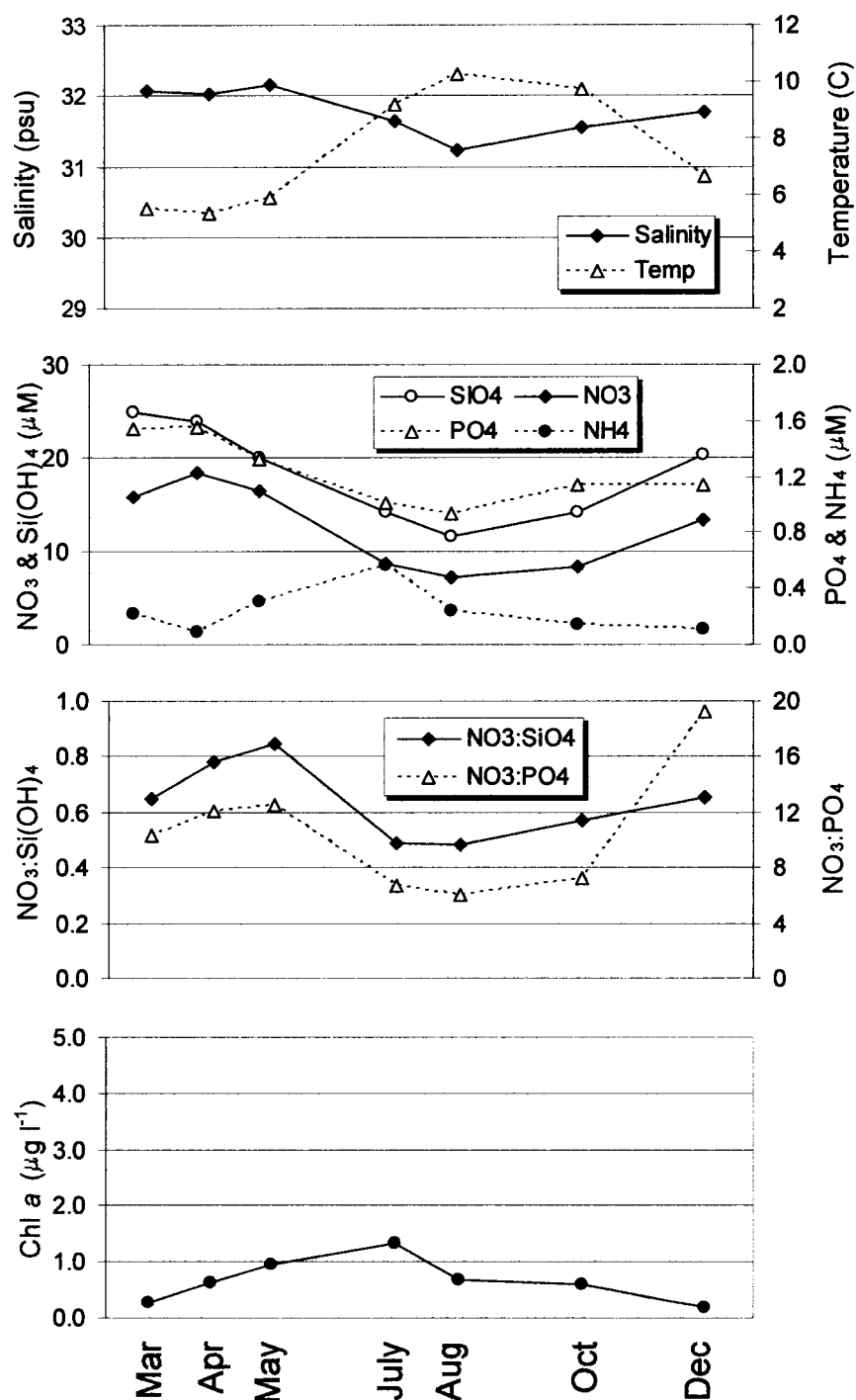


Figure 3.20 The 2001 annual cycle over the northern GOA shelf/slope from the upper 50 m means of salinity, temperature, nitrate, silicate, phosphate, ammonium, N:Si ratios, N:P ratios, and chl *a*.

Chapter 4. General Conclusions

4.1 Conclusions

The physical, chemical, and biological dynamics in the northern Gulf of Alaska (GOA) have proven to be very complex, both spatially and temporally. Some of the contributing factors are: the seasonal and interannual atmospheric dynamics, the climatic phases of ENSO and PDO, the degree of freshwater storage and discharge, the complex bathymetry and coastline, and the occurrence of large slope and small shelf eddies. The three year (1998, 1999, and 2000) nutrient data set from the Seward Line demonstrated a positive relationship between nutrients and salinity and established the extent to which the euphotic zone over the shelf/slope undergoes an annual cycle of nutrient drawdown in the spring and summer followed by replenishment in the fall and winter (see Figs. 2.2-2.16, 4.1-4.4). Phytoplankton biomass generally peaked in the spring and summer as the nutrient-rich euphotic zone stratified due to increasing freshwater discharge and solar heating. Nutrient concentrations were depleted or near depletion by summer in the surface waters with nutrient replete waters just below the pycnocline. The close proximity of nutrient-rich waters may partially explain this region's high productivity since brief mixing events, such as storms or eddies, could easily replenish the nutrient-poor surface waters. The data also demonstrated that the deeper waters experienced nutrient enrichment in the spring and summer in response to the onshore flux produced by the reduction in across-shelf transport associated with relaxed downwelling winds; thereafter, the nutrient-enriched bottom waters were mixed throughout the water column by winter winds and thermohaline processes (Chapman, 2000; Weingartner et al., 2005) (see Figs. 2.5a, 2.7-2.14, 4.2-4.4). This annual two-step process is believed to play a significant role in supplying nutrients to the euphotic zone thereby supporting primary productivity over the northern GOA shelf/slope.

A large degree of spatial variability was also found along the Seward Line in the timing, duration, and extent of nutrient drawdown and bottom enrichment. Nutrient drawdown and phytoplankton blooms appeared earlier in the near shore waters, which is

assumed to be due to earlier stratification from freshwater discharge in these regions (see Figs. 2.11-2.14, 4.3, and 4.4). Nutrient-poor conditions also prevailed longer into the fall in the coastal waters, which is also likely due to stronger stratification near shore. Silicate depletion was more prominent over the inner shelf than over the outer shelf and slope suggesting these waters are more heavily dominated by siliceous phytoplankton species. This data set also showed a large degree of interannual variability in the extent of nutrient replenishment/drawdown and phytoplankton growth (see Figs 2.11-2.14, 4.3, and 4.4). Much of this variability can be attributed to the climatic phases of ENSO and PDO, especially in staging the late winter/pre-bloom conditions. Spring conditions over the shelf appeared to be optimal in 2000 when pre-bloom nutrient concentrations were relatively high and the water column was strongly stratified due to comparably weak downwelling winds and high freshwater discharge (see Table 2.3 or 4.1). The potential impact of slope eddies on primary productivity also became very obvious in the spring of 1999 when unusually high phytoplankton biomass was measured over the outer shelf and slope in May 1999 (see Figs. 2.3, 2.13, 2.14. and 4.4).

New production calculated from nutrient drawdown for the Seward Line established that new production rates were highest near shore in the early spring. They were relatively high later in the spring off shore, which further substantiates the importance of stratification to the productivity of this region (see Table 2.2). The new production estimates from the northern GOA shelf were, overall, higher than estimates from Ocean Station Papa (OSP) in the HNLC subarctic North Pacific (Wheeler, 1993; Wong et al., 2002). This was expected when comparing a shelf region to an oceanic region.

A comprehensive examination of the 1998-2001 nutrient data including the supplementary cross-shelf transects and transects within Prince William Sound (PWS) in Chapter 3 provided answers to the following questions that were raised after examining the Seward Line in Chapter 2.

1) *Does the whole northern GOA shelf region experience nutrient limitation in the spring and summer?* Yes. The upper euphotic zone in PWS and over the shelf/slope

experienced nitrate and phosphate depletion in spring and summer (with earlier depletion in PWS and in the coastal shelf waters) (see Figs. 3.3, 3.5, 3.6, 3.8, 3.9, 3.11-3.13, 3.16, 3.19, 3.20, and 4.5). Given that the ammonium concentrations were observed to be small ($< 1.0 \mu\text{M}$) and the N:P ratios were low (< 5) in the upper euphotic zone throughout the study area in summer, this further indicates the phytoplankton community was limited by nitrogen during the summer months. The upper euphotic zone in PWS and in the coastal shelf waters also experienced silicate depletion in the spring and summer.

2) *Does the whole northern GOA shelf region experience a summer onshore flux of deep, high salinity, nutrient-rich slope water?* Yes. The bottom waters along all of the various cross-shelf transects upstream and downstream of the Seward Line and in PWS were enriched in salinity and nutrients in the spring and summer (see Figs. 3.3, 3.5, 3.8, 3.9, 3.11, 3.13, 3.16, and 4.5).

3) *And if so, is it uniform or variable spatially?* Nutrient enrichment at depth is variable along and across the shelf and appears to be largely determined by the local bathymetry. For example, in the spring and summer months, bottom salinities and nutrient concentrations were consistently higher in Hinchinbrook Canyon than over other regions of the shelf (see Figs. 3.3, 3.5, 3.8, 3.9, 3.11, 3.13, 3.16, and 4.5).

4) *Do nutrient reservoirs form over other regions of the northern GOA shelf in addition to the inner shelf portion of the Seward Line?* Yes. Comparably high near bottom nutrient concentrations were measured in Hinchinbrook Canyon and in the deeper regions of the shelf upstream of PWS off Cape Suckling (see Figs. 3.6, 3.8, 3.9, 3.10, 3.11, 3.13, and 4.5).

5) *How do the physical structure and the nutrient-phytoplankton dynamics in PWS compare to those over the northern GOA shelf/slope?* In 2001, nutrient drawdown and depletion in the upper euphotic zone occurred earlier in the spring in PWS than over the shelf/slope and was accompanied by a stronger spring phytoplankton bloom (see Figs. 3.19, 3.20, and 4.6). As found over the shelf/slope during the summer months, nutrient concentrations were replete within and just below the euphotic zone and nutrient enrichment was evident in the deeper waters in PWS.

6) *Are there any prevailing spatial nutrient dynamics over the GOA shelf/slope or in PWS?* Yes. Along-shelf trends were found in the upper coastal waters in the winter and spring with salinities, temperatures, and nutrient concentrations decreasing downstream (see Figs. 3.14, 3.15, and 4.7). This indicates the upper coastal shelf water properties are directly influenced by coastal features and PWS potentially acts as a sink for inorganic nutrients. In PWS, the northwestern stations within Montague Strait were more strongly stratified with earlier, stronger nutrient drawdown and phytoplankton blooms due to the prevailing western boundary flow of the Alaska Coastal Current passing through PWS (see Figs. 3.6, 3.8, and 3.10) .

7) *How do mesoscale slope eddies affect nutrient-phytoplankton dynamics over the outer GOA shelf and slope?* The passing of mesoscale slope eddies generally induced upwelling over the shelf break and slope; however, there was commonly no apparent effect on the nutrient-phytoplankton dynamics. The most obvious exception presented itself in the spring of 1999 when upper euphotic zone nutrient concentrations were reduced by a very strong phytoplankton bloom associated with the passing of a slope eddy (see Figs. 2.3, 2.13, 2.14, 3.12, 3.18, and 4.4).

Overall, the northern GOA shelf was found to be a very dynamic region with a large degree of spatial variability. The nutrient dynamics in the upper shelf/slope waters are affected by coastal inputs, flow patterns of the ACC and the Alaskan Stream, frontal features, shelf eddies such as the Kayak Eddy, passing slope eddies, and Prince William Sound. At depth, nutrient dynamics over the shelf/slope are most strongly influenced by the bathymetry and seasonal onshore flux. The northern GOA shelf/slope is a very dynamic region that requires many more years of research and monitoring to fully understand the reasons why this shelf is so biologically productive.

4.2 Future directions

The information attained from this four year data set has provided a general knowledge of the nutrient distributions over the northern GOA shelf/slope and in PWS. We know nutrient concentrations generally increase with depth and distance offshore and

the upper and lower waters undergo a general annual cycle. We also know however, there is a large degree of temporal and spatial variability in the nutrient distributions. Some of the reasons for this variability that we are just beginning to identify are: the climatic phases of ENSO and PDO, the complex coastline and bathymetry, variability in freshwater discharge, variability in the wind regimes, variability in the ACC and the Alaska Stream flows and their frontal features, and the occurrence of small eddies and meanders over the shelf and large mesoscale eddies over the shelf break and slope. This shelf region has proven to be very dynamic; therefore, continued research needs to be conducted in order to better understand the mechanisms and dynamics that are driving the biological productivity of this region.

The primary objective of this research and for the larger GLOBEC program that supported this research is determining the source and movement of the major nutrients in this biologically production region, especially to the coastal euphotic zone which generates elevated phytoplankton biomass. We know nutrient concentrations are replete in the deeper waters throughout the year and are replenished in the upper waters during the winter months, before and after the growing season. However, we do not fully understand the mechanisms delivering nutrient-rich waters to the upper coastal waters considering this is a predominantly downwelling shelf. In addition to the prior sampling design, which consisted of several cruises each year for several years, sampling specific locations continuously or regions synoptically with physical/chemical moorings and mesoscale surveys would be beneficial. A continuation of the prior sampling design would continue to capture the seasonal and interannual variability over a larger spatial scale while the addition of moorings and mesoscale surveys would provide insight into the shorter-term, local dynamics at work in this region.

Bio-physical moorings equipped with physical, chemical, and biological sensors successfully collected data at station GAK 4 from March 2000 through March 2002 (<http://www.ims.uaf.edu/salmon/GAK4/gak4.html>). The preliminary results presented the annual cycles containing the short-term variability in the physical, chemical, and biological properties. They also confirmed the importance of stability in the initiation of

the spring phytoplankton bloom. Two cruises in the spring and summer of 2003 conducted mesoscale and finescale surveys where physical, chemical, and biological data were collected along closely spaced cross-shelf transects through the use of a SeaSoar. The preliminary results illustrate the large degree of spatial variability in the surface (5 m) salinity, nitrate, and chlorophyll *a* distributions in both the coastal and offshore water (<http://www.ims.uaf.edu/salmon/mesoscale/mesoscale.html>). These preliminary results have demonstrated the degree of temporal and spatial variability experienced by this shelf region; therefore, the continued collection of such data is needed to determine the mechanisms behind this variability and its effects on the biological ecosystem.

Monitoring of the various canyons and troughs throughout the study area would aid in determining their role in the transport of deep, nutrient-rich waters onshore. Mooring deployments in Hinchinbook Canyon, Bainbridge Trough, and/or Resurrection Canyon would provide detailed records of the flow directions and speeds at depths through the water column throughout one, or preferably many, annual cycles. This would provide further insight into the role of these bathymetric features and the degree of local variability. More thorough monitoring of the physical, chemical, and biological properties in the entrances to PWS would help us to better understand how PWS interacts with the shelf and how effectively PWS influences the shelf dynamics. In addition, more thorough along-shelf sampling of the coastal inner shelf region is needed to determine the extent and cause of spatial variability in the Alaska Coastal Current expressed as meanders, eddies, and frontal instabilities and their impacts on nutrient distributions and biological productivity. Nutrient concentrations in the various coastal freshwater sources (rivers, glaciers, bays, runoff) also need to be analyzed to better determine the coastal nutrient supply.

Other regions that should be more thoroughly monitored, either through the use of mooring or mesoscale surveys, are the shelf breaks and continental slopes. Shelf breaks are generally regions of enhanced productivity; therefore, a closer examination of the shelf break dynamics would be beneficial. The shelf break was only routinely sampled along the Seward Line, which only provided a few snapshots from one location

throughout the years and seasons. Therefore, the spatial and temporal shelf break frontal dynamics need much more comprehensive sampling. For instance, the movement and/or fluctuation of the shelf break front throughout the year nor the affect of passing slope eddies on the shelf break front is understood. Further studies need to address how upwelling associated with these slope eddies affects the shelf break front and if upwelling enhances the onshore advection of deep, nutrient-rich waters onto the shelf. These phenomena have clearly demonstrated the potential to drastically increase primary productivity; therefore, it is important that we examine these events in order to understand what specific conditions result in enhanced primary productivity. These slope eddies are generated in the eastern and northern GOA and their generation is linked to ENSO events (Okkonen, 2001). With the use of near-real-time altimetry data and SeaWiFS images displaying ocean color researchers can now successfully locate, sample, and monitor these oceanic phenomena.

We have learned that the northern Gulf of Alaska shelf harbors a large degree of spatial and temporal variability. With continued research through long-term observation programs, mesoscale surveys, bio-physical moorings, and modeling efforts we will be better able to identify and understand the physical mechanisms driving the physical and chemical properties that support and promote the biological productivity of this unique shelf. From those findings we may better understand the implications of climate change on this ecosystem and possibly predict the consequences of climate change on the production, abundance, and distribution of the upper trophic level marine organisms.

4.3 References

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Table 4.1 A summary of winter physical conditions, March nitrate concentrations, and phytoplankton biomass in the spring of 1998, 1999, and 2000.

	Downwelling Winds	Freshwater Discharge	Stratificati on	March [NO ₃ ⁻]	Phytoplankton Biomass
1998 (El Niño)	Strong	High	Strong	Lowest	
1999 (La Niña)	Average	Low	Weak		Highest (slope)
2000	Weak	High	Strong	Highest	Highest (shelf)

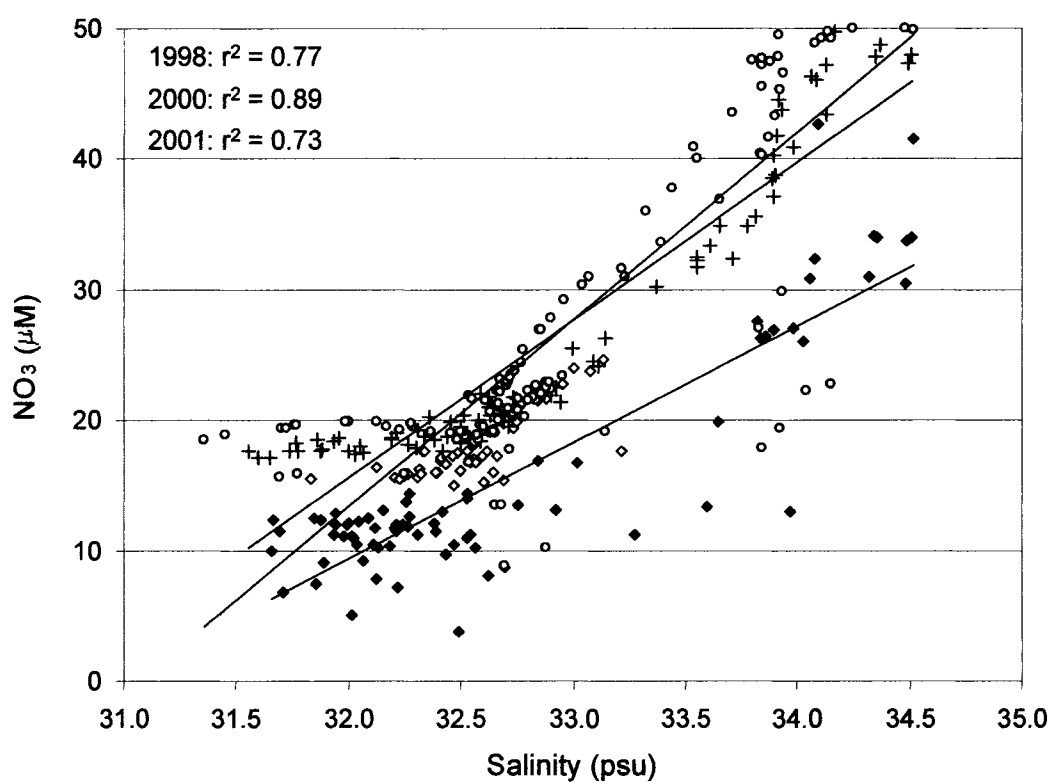


Figure 4.1 Salinity and nitrate relationships at depths > 75 m for March 1998 (\blacklozenge), March 1999 (\diamond), March 2000 (+), and March 2001 (\circ). Regressions lines and r^2 values are shown for March 1998, March 2000, and March 2001.

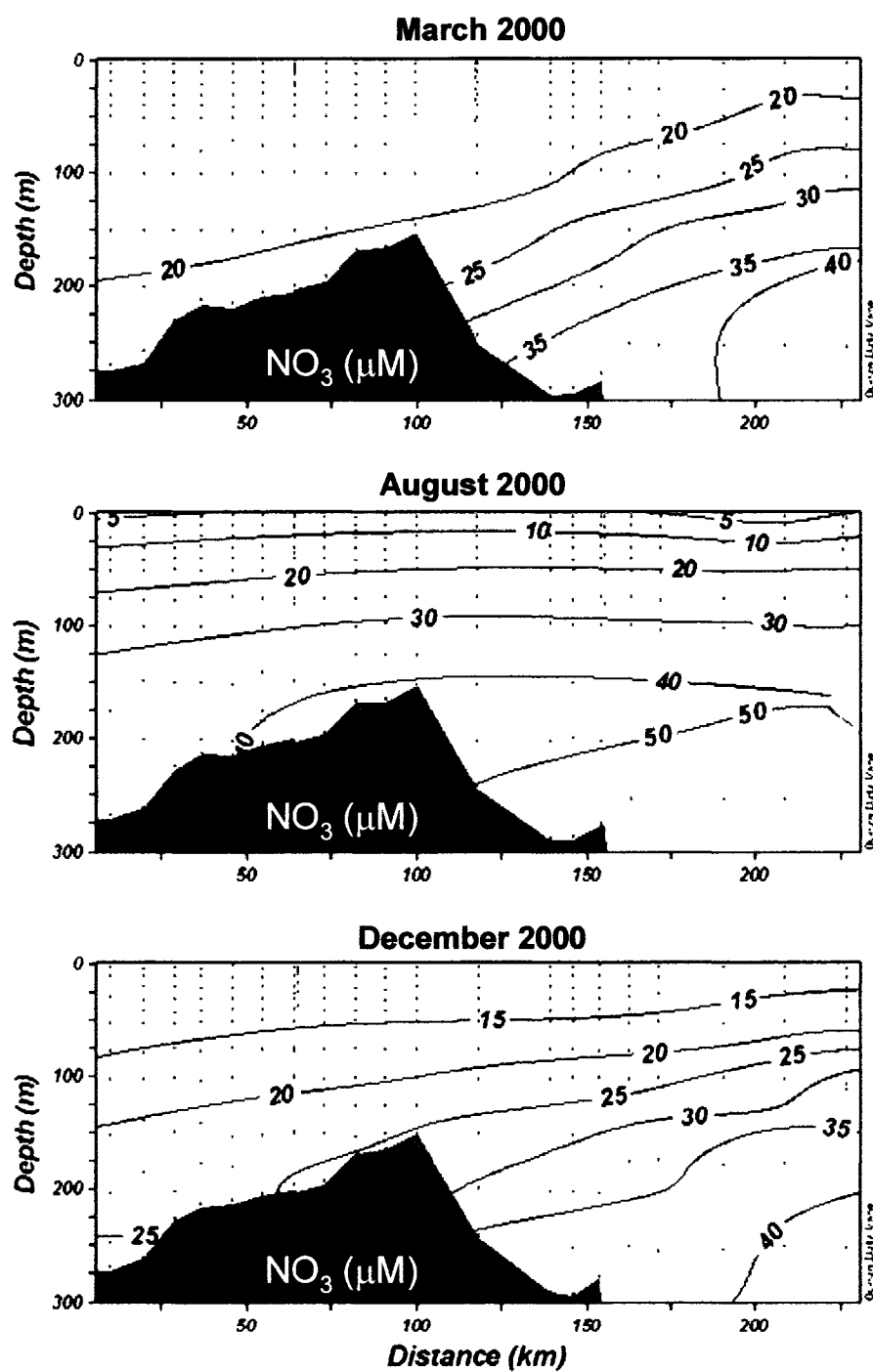


Figure 4.2 Vertical profiles of nitrate across the Seward Line taken March, August, and December 2000. Units are μM for nitrate.

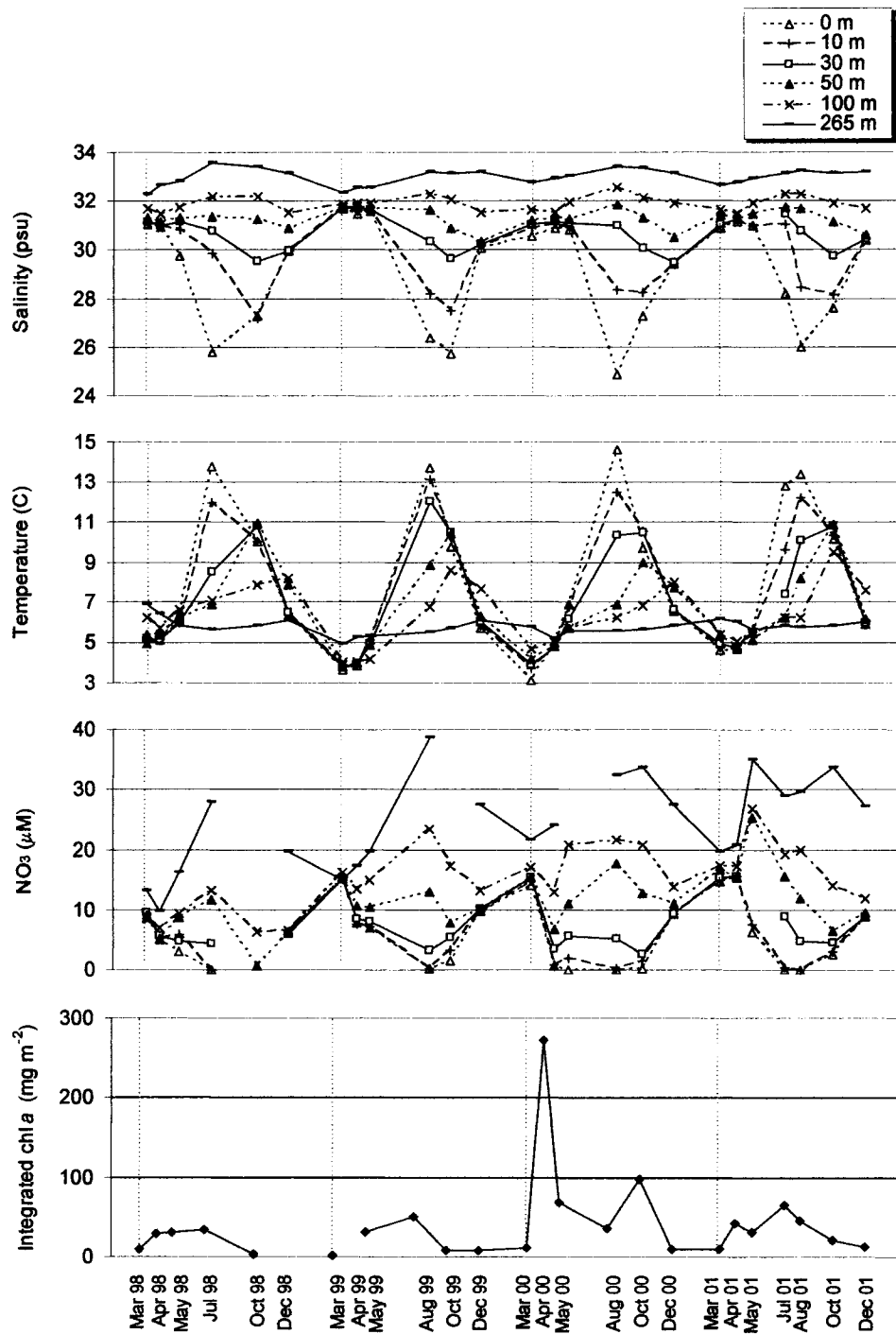


Figure 4.3 Time series at GAK 1 of salinity, temperature, nitrate and integrated chlorophyll *a* concentrations (0-50 m) March 1998 – December 2001. Dashed lines indicate March data.

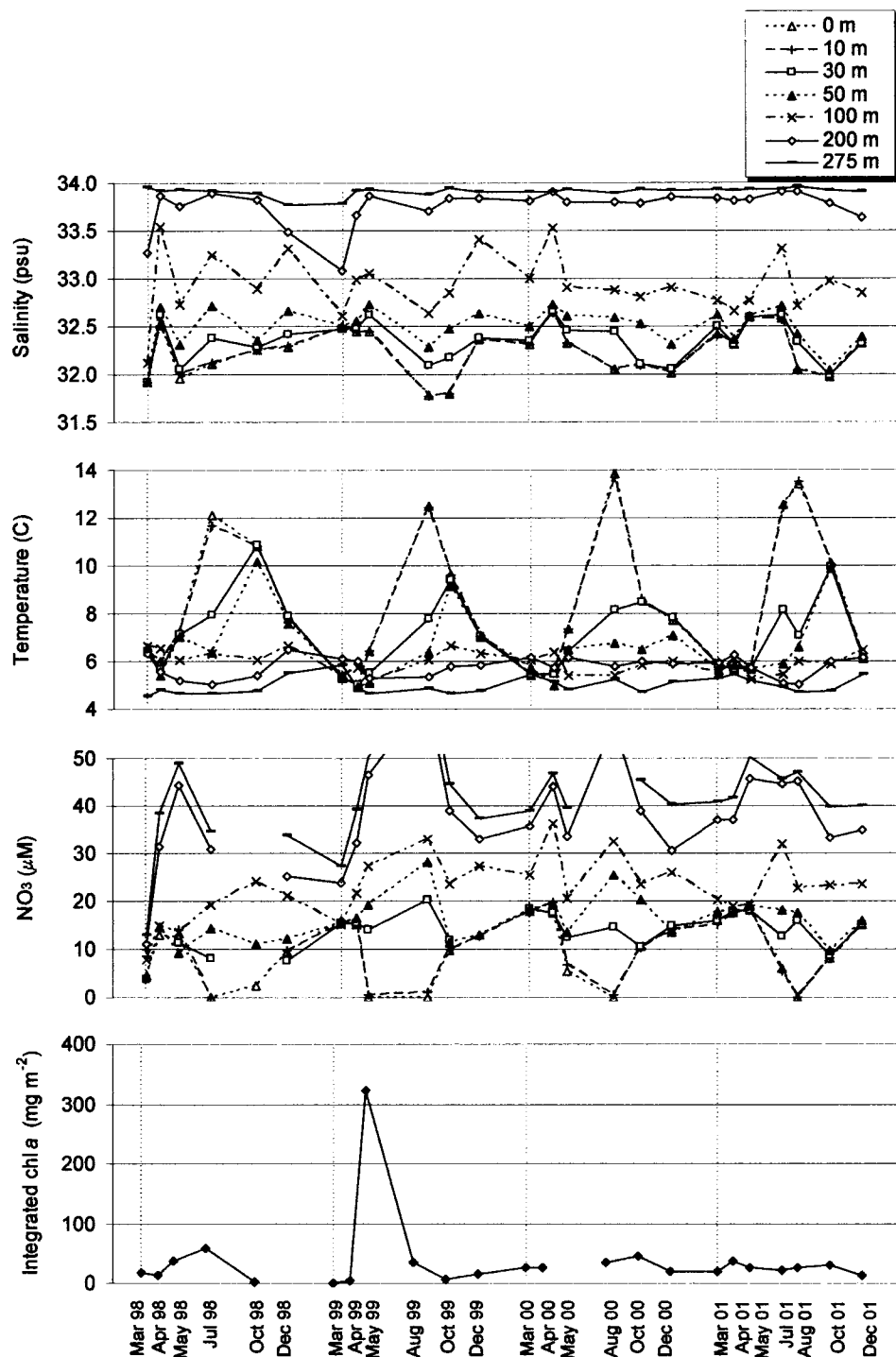


Figure 4.4 Time series at GAK 9 of salinity, temperature, nitrate and integrated chlorophyll *a* concentrations (0-50 m) March 1998 – December 2001. Dashed lines indicate March data.

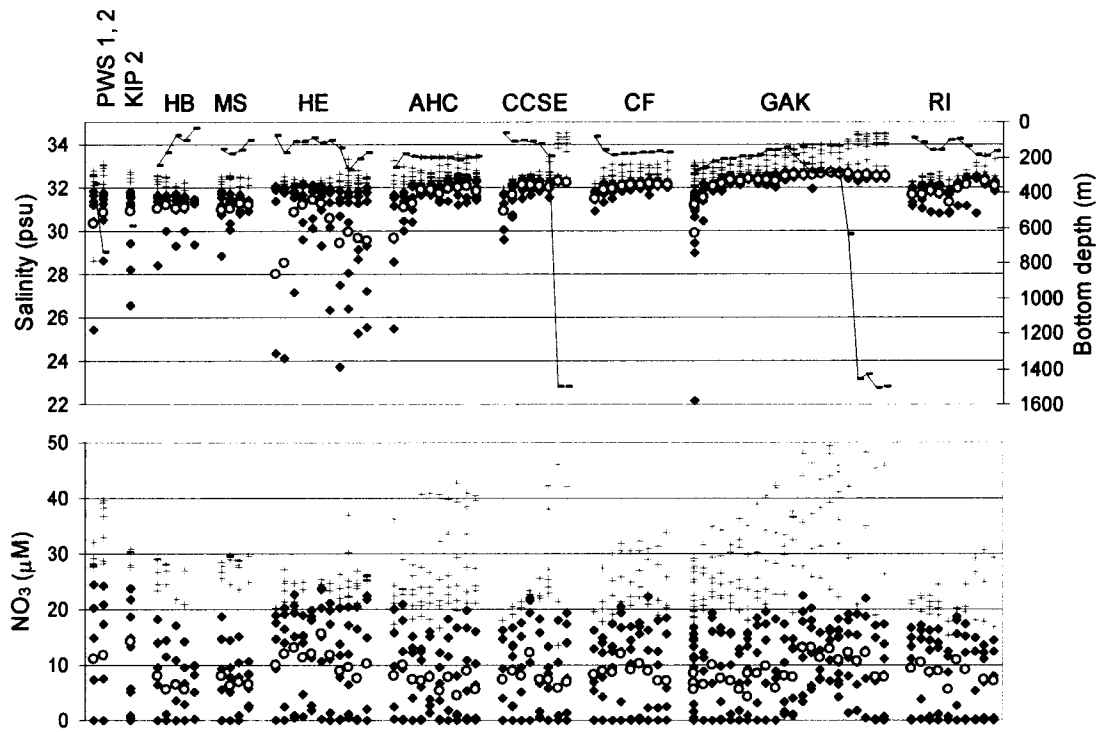


Figure 4.5 Scatter plots of salinity, bottom depth, and nitrate data collected from PWS and the northern GOA in July 2001. (+ = data > 50 m, ♦ = data < 50 m, and O = upper 50 m means)

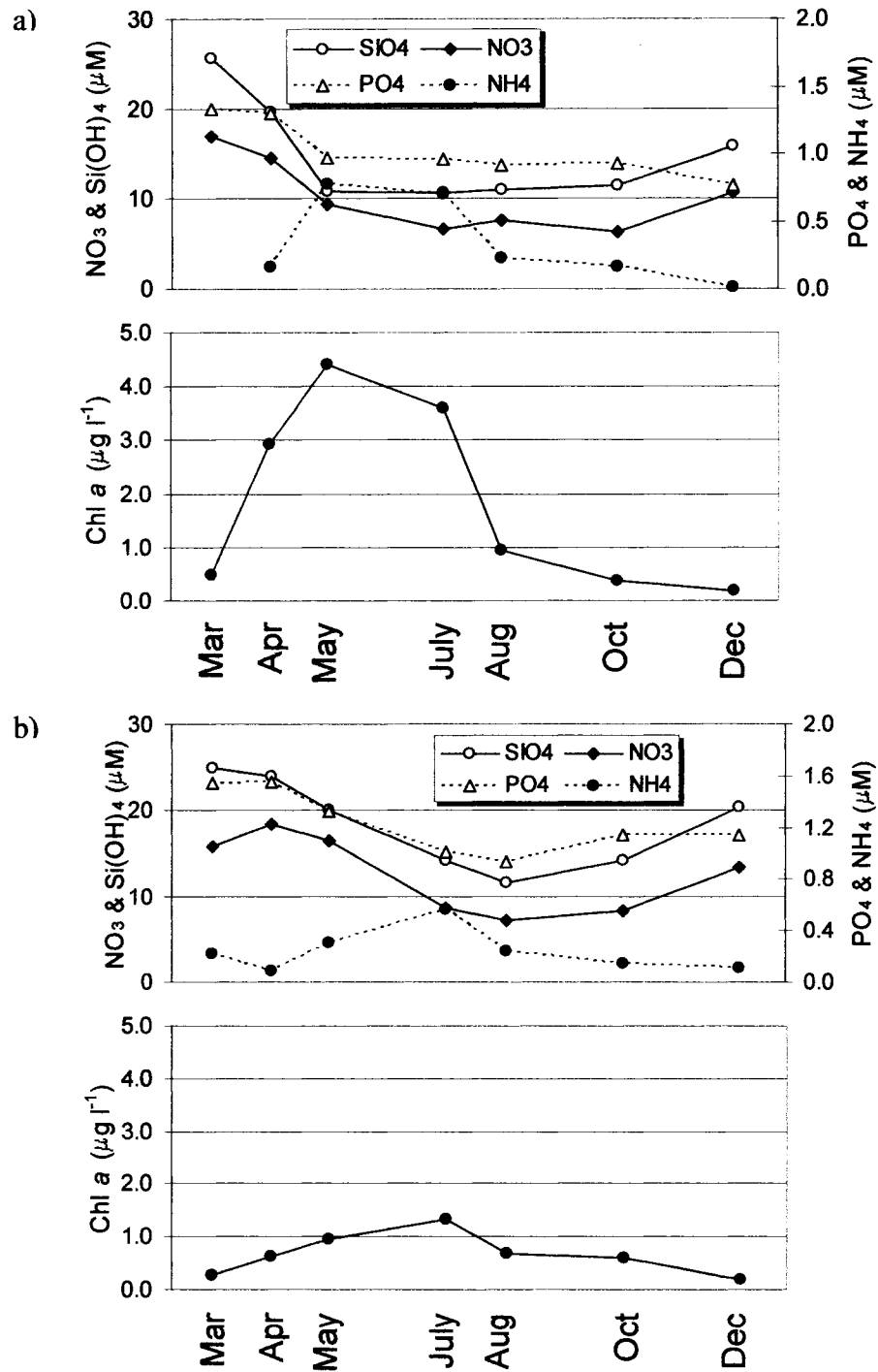


Figure 4.6 The 2001 annual cycle a) in PWS and b) over the northern GOA shelf/slope from the upper 50 m means of nitrate, silicate, phosphate, ammonium, and chl *a*.

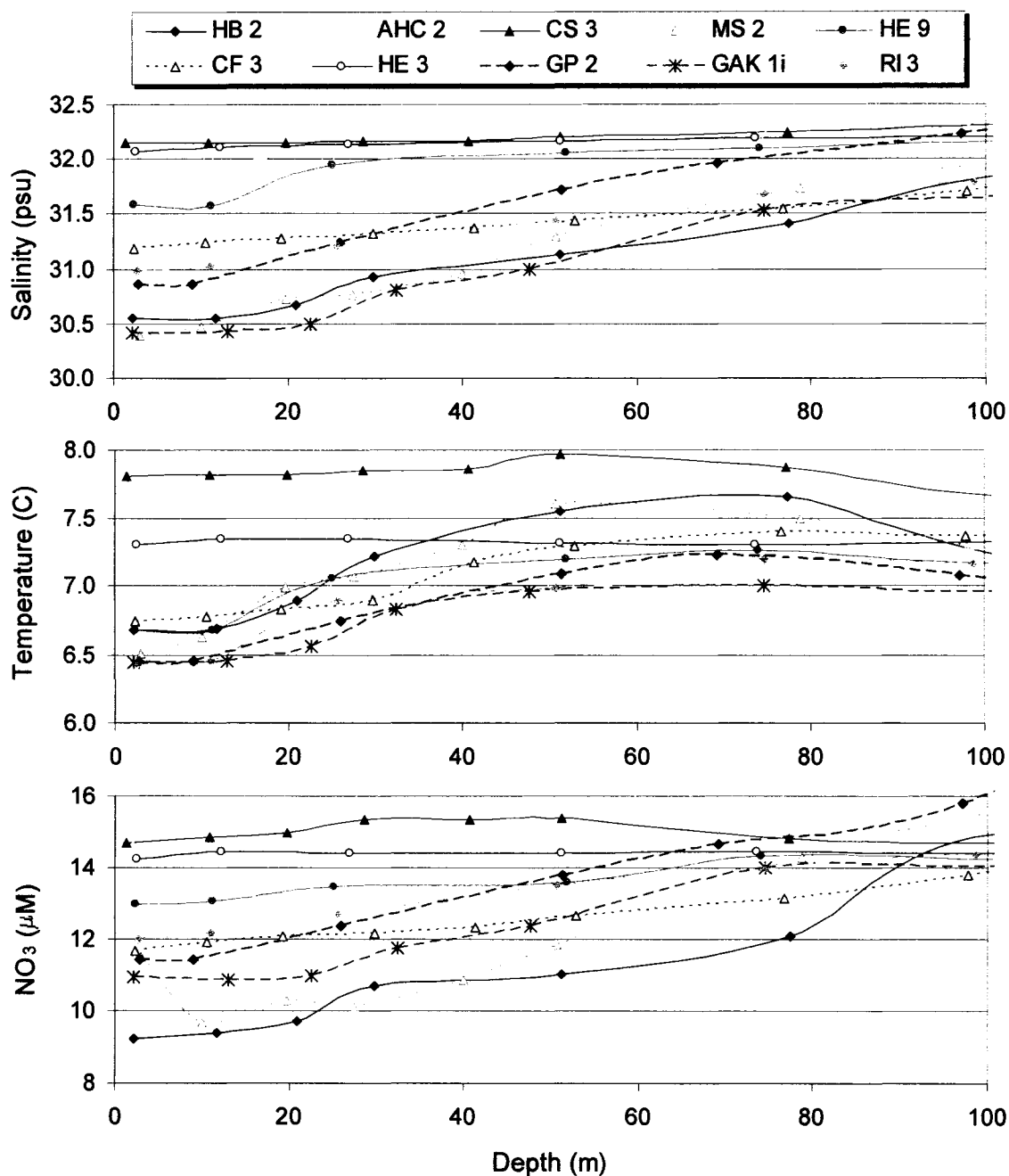


Figure 4.7 Upper 100 m profiles of salinity, temperature, and nitrate collected from near shore shelf stations in December 1999.